Manufacturing Cost Analysis of 1 kW and 5 kW Solid Oxide Fuel Cell (SOFC) for Auxilliary Power Applications

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Executive Summary

Background

Under a cooperative agreement with the Department of Energy's (DOE's) Fuel Cell Program, Battelle has been tasked to provide an independent assessment of fuel cell manufacturing costs at varied volumes and alternative system designs.

This report provides cost estimates for the manufacture of 1 kW and 5 kW solid oxide fuel cells (SOFC) designed for auxiliary power unit applications using high-volume manufacturing processes at annual production volumes of 100, 1000, 10,000, and 50,000 units.

Aproach

Battelle's cost analysis methodology is a four-step approach:

Step 1 – Market Assessment. In this step, we identified the operational and performance requirements (e.g., hours of operation, frequency, lifetime expected) of the target application and market. This information formed the basis for selecting the right system design and fuel cell type for user requirements and the appropriate production volumes to consider in the modeling exercise.

Step 2 – System Design. A fuel cell auxialliary power unit design was developed as a system representative of typical design based on literature, manufacturer feedback and engineering expertise of Battelle.

Step 3 – Cost Modeling. Battelle gathered vendor quotes for material costs, production equipment, and outsourced components. Custom manufacturing process models were defined where necessary and parametrically modeled based on knowledge of the machine, energy and labor requirements for individual steps that comprise the custom process.

Step 4 – Sensitivity Analysis/Lifecycle Cost Analysis. A sensitivity analysis was performed to determine which design parameters or assumptions have the most effect upon the stack and system cost. Lifecycle costs of the fuel cell APU were compared to equivalent technologies in the market today.

Results

Overall the final cost was analyzed in four distinct categories: the capital cost of manufacturing equipment, the direct cost of material and assembly of the stack, the expense of balance of plant hardware, and the final cost of complete system assembly and testing it.

The primary driver of overall APU system cost is the Balance of Plant hardware, accounting for 63-88% of total system costs across the production volumes analyzed. The complex nature of onboard fuel reforming and the high temperature requirments for Solid Oxide Fuel Cell operation keep the part count and material costs high.

The stack costs is most sensitive to change in metal components, as the quantity of high temperature steel makes up the bulk of the stack cost. BOP costs are most sensistive to heat transfer and power conversion equipment; specifically, the amount of heat transfer required to heat fuel feed streams, cool reformate for desulfurization and reheat upstream of the stack is significant.

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1 Introduction

Battelle is conducting manufacturing cost assessments of fuel cells for stationary and non-automotive applications to identify the primary cost drivers impacting successful product commercialization. Battelle, under a 5-year cooperative agreement with the Department of Energy's (DOE's) Fuel Cell Program, will provide an independent assessment of fuel cell manufacturing costs at varied volumes and alternative system designs. This report provides cost estimates for the manufacture of 1 kW and 5 kW solid oxide fuel cells (SOFC) designed for auxiliary power unit applications. This report identifies the manufacturing costs of fuel cells using high-volume manufacturing processes at annual production volumes of 100, 1000, 10,000, and 50,000 units. The system design and manufacturing volumes were defined using Battelle's fuel cell system integration expertise and refined through a discussion with industry partners. The report presents our approach; the design of the system, design assumptions, and manufacturing processes modeled using the design for manufacturing assembly (DFMA™) software; costs of the system, sub-system, and specific components; the main cost drivers identified through a sensitivity analysis; and a summary of opportunities for cost reduction.

2 Approach

Battelle's cost analysis methodology is a four-step approach (Figure 2-1):

Step 1 – Market Assessment

Step 2 – System Design

Step 3 – Cost Modeling

Step 4 – Sensitivity Analysis/Lifecycle Cost Analysis.

This approach has been successfully applied to previous cost analyses developed by Battelle.[1,2]

[1] Battelle. 2011. The High Volume Manufacture Cost Analysis of 5 kW Direct Hydrogen Polymer Electrolyte Membrane (PEM) Fuel Cell for Backup Power Applications. Contract No. DE-FC36GO13110.
[2] H. Stone, K. Mahadevan, K. Judd, H. Stein, V. Contini, J. Myers, J. Sanford, J. Amaya, and D. Paul. 2006. Economics of Stationary Proton Exchange Membrane Fuel Cells, Interim Report. Contract No. DE-FC36GO13110.

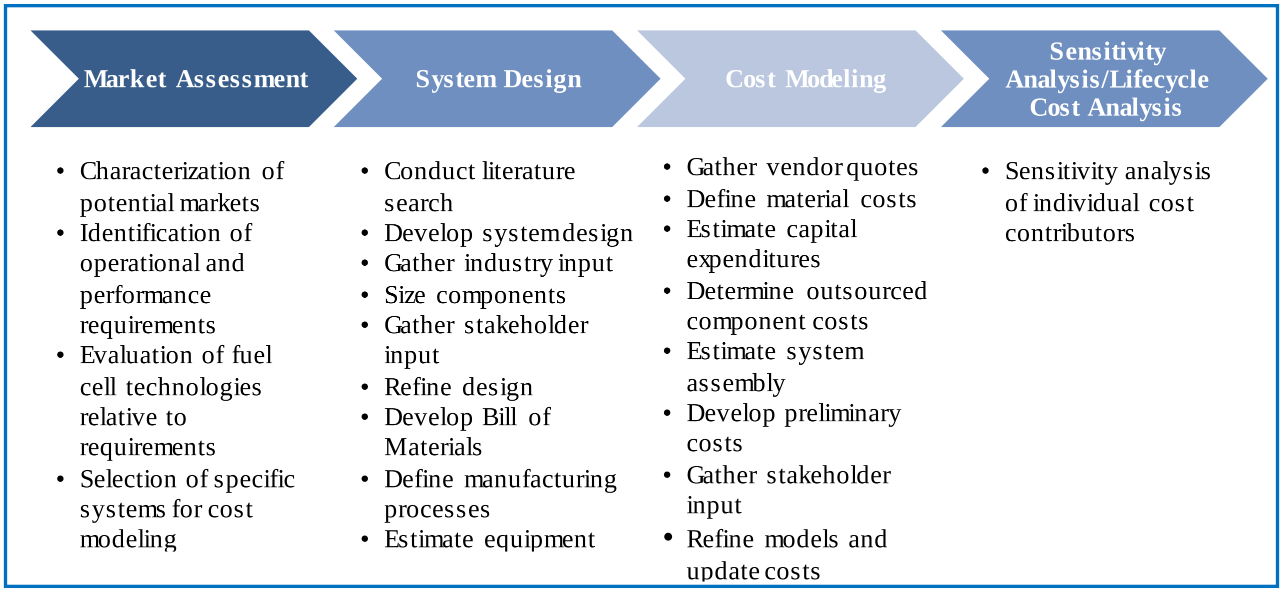

Figure 2-1. Battelle's Cost Analysis Approach

The first step in our methodology, ***Step 1 Market Assessment***, is to ensure that we select the right fuel cell type and appropriate production volumes to meet market requirements. In this step, we identified the operational and performance requirements (e.g., hours of operation, frequency, lifetime expected) of the target application and market. Using this information, an assessment of the user requirements for a fuel cell product was defined. We also completed a quick survey of the market through an industry dialogue to estimate the number of units in the market and the expected market growth for fuel cells in auxiliary power unit applications. This information formed the basis for selecting the right system design and fuel cell type for user requirements and the appropriate production volumes to consider in the modeling exercise.

Step 2 System Design, , a literature review of fuel cell designs for auxiliary power unit applications, component design and manufacturing processes, possible improvements in system design and manufacturing was completed. From these results the basic construction and operational parameters for a fuel cell stack and system were defined as well as potential improvements. The fuel cell design developed does not focus on an individual manufacturer's designs, but a system representative of typical design based on literature and engineering expertise of Battelle. The stack and the system design were vetted with industry stakeholders to ensure feasibility of the design, to identify possible improvements, and to determine current and alternate manufacturing approaches. A finalized design and projected improvements form the basis for developing the bill of materials (BOM). Decisions were then made about which components would be manufactured internally and which would be outsourced. For internally manufactured components (including applicable balance of plant (BOP) components), manufacturing processes and production equipment are defined in detail.

In ***Step 3 Cost Modeling***, Battelle gathered vendor quotes for material costs, production equipment, and outsourced components. Custom manufacturing process models were defined where necessary and parametrically modeled based on knowledge of the machine, energy, and labor requirements for individual steps that comprise the custom process. The sequence of actions required to assemble the components and test the final fuel cell system were developed and analyzed for cost reduction opportunities through component consolidation and process optimization. Manufacturing quality control required was based on suggestions of equipment vendors and Battelle's experience with product manufacturing. Outsourced components costs were estimated through vendor quotes. Mathematic functions for scaling factors were developed to estimate the changes to outsourced components and material costs with production volumes when vendor quotes for higher volumes are not available. These were derived using engineering rules of thumb and estimates from other manufacturing processes and considered impacts on system design. Using the Design for Manufacturing Assembly (DFMA™) software, component costs calculated from both custom and library manufacturing processes and the outsourced components were incorporated into the assembly and test sequence models to determine the final cost of producing the fuel cell systems. The output of the DFMA™ models were also used to calculate production line utilization to determine the number of individual process lines required to support various product demand levels, as input to the manufacturing capital cost model. Capital equipment expenditures for production were amortized over a 20-year period and the annual amortized cost will be distributed over production volume for that year. Financial assumptions that were used are consistent with the DOE Hydrogen Analysis (H2A) model. Total stack system costs including capital expenditures were then estimated for the baseline system and projected improvements.

In ***Step 4 Sensitivity Analysis***, a sensitivity analysis was performed to determine which design parameters or assumptions have the most effect upon the stack and system cost. Single factor sensitivity analysis was performed. Single factor sensitivity analysis helps determine the impact of individual parameters on system costs. Based on these results, insights into the design optimization of fuel cell systems are provided to reduce the total system cost and total cost of ownership.

3 Market Assessment

In 2012 Battelle performed a market analysis to support the selection of the system and fuel cell type for the cost analysis. [3] For this study, Battelle focused on fuel cell systems for auxiliary power applications on transportation equipment (RV, truck, aircraft,watercraft). Battelle reviewed commercial auxiliary power units to gain a general understanding of the characteristics and equipment types available in the market. Battelle gathered information on the operational and performance requirements for a range of APU applications. This assessment included consideration of the characteristics of deployed APU systems, including fuel cell technologies. Characteristics of interest included:

- Application
- Types of equipment currently used
- Load capability/system size
- Hours of use
- Reliability/durability performance or requirements

[3] Battelle, 2012. Task 2: Market and Application Requirements to Support Fuel Cell Design: Auxiliary Power Units Report to the DOE. DOE Contract No. DE-EE0005250/001.

Sources of information included:

- Previous analyses and research
- Fuel cell manufacturers
- APU equipment manufacturers and end-users
- Industry Associations
- Journal articles
- Internet searches

3.1 Transportation APU Market Summary

Four main markets for APUs are recreational vehicle (RV), commercial trucking, aviation, and maritime. Additional market applications with the potential to use APUs include trains, mobile medical care vehicles (ambulance and similar), and the entertainment industry. Currently available APUs are powered by internal combustion (IC) engine generators (spark ignition, diesel), gas turbines, and batteries.

Table 3-1 summarizes the market characterization performed by Battelle including typical APU power sources, sizes, and specific market drivers. For all markets a value proposition can be made based on the well-known advantages of fuel cell technologies including higher efficiency, decreased emissions, and lower noise. Table 3-1 identifies additional market drivers that would further encourage market adoption of fuel cell APUs.

Table 3-1. Market Summary for APU Applications

Market Application	Current APU Types	Standalone APU Size Range	Specific Commercial Market Drivers for Fuel Cell Technology
Recreational Vehicle (RV)	Battery IC Engine Fuel Cell	1-12 kW (standalone) As low as 50 to 100 W (hybrid) [4]	Campsite quiet-hour regulations
Commercial Truck	Battery IC Engine Fuel Cell	1 to 7 kW (standalone APU) 1 to 5 kW (hybrid APU) 10 to 20 kW (mobile refrigeration)[5]	Evolving local and national noise and emission regulations[6,7]
Aviation	IC Engine (Gas Turbine)	100 to 450 kW (traditional APU) 10 to 100 kW (peak reduction)	Notably low efficiency (15%) of existing APUs[8] Increased demand from More-Electric-Aircraft (MEA) and future All Electric Aircraft (AEA)
Maritime	Battery IC Engine	5 to 500 kW (small, including leisure)[9] 100 kW to 5 MW (commercial)[10]	NA

Regulatory market drivers will facilitate the rapid adoption of commercial truck APUs, particularly those with advantageous noise and emissions characteristics. The truck APU market has also been the primary focus of fuel cell manufacturers. Detailed product specifications for several existing APUs for Commercial Truck applications are listed in Table 3-2. Peak power requirements were not available for individual units. However, manufacturers provided general peak power requirements of 4-6 kW for commercial trucks. Physical dimensions, weight, and maintenance requirements are important considerations as well. APU power modules must be designed to fit onboard a vehicle without significantly restricting available space or fuel economy.

[4] "Frequently Asked Questions," Energy For You, http://www.efoy.com/en/mobile-homes-faqs.html.
[5] "Markets for Fuel Cell Auxiliary Power Units in Vehicles: A Preliminary Assessment, Louisiana Transportation Research Center, http://www.ltrc.lsu.edu/TRB_82/TRB2003-001443.pdf
[6] "Clean Air Nonroad Diesel – Tier 4 Final Rule, US Environmental Protection Agency, http://www.epa.gov/nonroad-diesel/2004fr.htm.
[7] American Transportation Research Institute Compendium of Idling Restrictions, January 2012.
[8] Spenser, J., "Fuel Cells in the Air," Boeing Frontiers, Vol. 03, Issue 3, July 2004, online edition, http://www.boeing.com/news/_frontiers/archive/2004/july/ts_sf7a.html.
[9] Kohler Marine Generators product description, Continental Generators online catalog, http://www.continentalgenerators.com/_kohler-marine-generators.html.
[10] Hoffman, D., "System Design: Lessons Learned, Generic Concepts, Characteristics & Impacts," US Department of Energy, Energy Efficiency & Renewable Energy, Office of Naval Research, http://www1.eere.energy.gov/hydrogenandfuelcells/_pdfs/apu2011_11_hoffman.pdf.

Table 3-2. Existing Product Specifications for a Sample of Commercial Truck APUs

Technology	Manufacturer & Model	Power Module Lifetime*	Net Power Output	Dimensions (L x W x H) cm	Weight kg	Retail Price	Power Density (W/L)	Specific Power (W/kg)
Diesel engine	Willis Power Systems,Willie Compact	50,000 hours (>10 years) Warranty: 2 yrs	4 kW	60 x 69 x 56	82	$8,500	17	22
Diesel engine	Thermo King, Tripac	Warranty: 1 yr	2.2 kW with an option for 4 kW	71 x 56 x 61	88	$7,700	16	20
Diesel engine generator, alternator	Carrier, Comfort Pro	Warranty: 2 yrs/4,000 hrs	4 kW	47 x 64 x 71	77	$8,100	19	23
Diesel engine	Diamond Power Systems	Warranty: 2 yr/4,000 hrs	6.5 kW	72 x 54 x 75	95	$7,600	22	31
Battery (deep cycle)	Synergy APU, Comfort CAB	Warranty : 2 yr 6 batteries replaced approx. every 3 yrs	Approx. 400 Amp-hours at 12 VDC	33 x 17 x 24	66 (batter-ies only)	$3,700	NA	NA

*Lifetime of the power module was not available for many conventional-powered APUs. Where available, warranty information is provided as a substitute

Fuel cell APUs are being developed to run on a range of different fuels, including hydrogen, methanol, LPG (liquefied petroleum gas), JP-8, and ultra-low-sulfur-diesel (ULSD). Fuel cell development has followed multiple technology paths, including direct methanol fuel cells (DMFC), SOFC, and both standard (80°C) and high temperature (160°C) proton exchange membrane fuel cells (PEM and HTPEM respectively). DMFC APUs run on methanol and do not require a reformer. SOFC and PEM APUs usually incorporate a fuel reformer built into the unit so that the system can run on reformate from readily available liquid fuels. Standard temperature (80°C) PEM APUs require pure hydrogen which implies on-board hydrogen storage or more expensive reformers.

In response to the market drivers, fuel cells have begun to emerge as an alternate power source for some APU applications. Significant market penetration has not yet been achieved. Fuel cell APUs represented 20 percent of all fuel cell systems shipped in 2010. In 2010, global fuel cell APU shipments reached approximately 3,100 with over 99% of those systems manufactured in Europe[11].

Table 3-3 summarizes the commercial deployments and technology demonstrations of fuel cell APUs identified in the literature review. Supporting information for the demonstration programs can be found on the websites for the U.S. Department of Energy's Office of Energy Efficiency and Renewable Energy website[12], Fuel Cells 2000[13], or the U.S. Solid State Energy Conversion Alliance[14].

[11] Pike Research, Fuel Cells for Auxiliary Power Unit Applications, 2011.
[12] http://energy.gov/eere/office-energy-efficiency-renewable-energy
[13] http://www.fuelcells.org/
[14] http://www.netl.doe.gov/technologies/coalpower/fuelcells/seca/

Table 3-3. Summary Information for Fuel Cell APU Applications

Equipment Type	Fuel Cell Type	System Size	Market Status
Recreational Vehicle	DMFC battery charger	<0.1 kW	Over 17,500 EFOY units manufactured by SFC Energy sold between 2007 and 2010, primarily in Europe.
	SOFC	125W	Protonex product offering withdrawn to facilitate focus on military applications.
	PEM	1 kW	Voller Energy product offering withdrawn by manufacturer.
Commercial Truck	SOFC	3-5 kW	Technology demonstrations and development by many, including Delphi, Cummins, and UC Davis.
	PEM	1-6 kW	
Aviation	SOFC and PEM	10 kW	Limited to technology development & demonstration programs – no deployed products.
Maritime	SOFC PEM HTPEM	5-30 kW 5-15 kW 13-50 kW	Limited to technology development & demonstration programs – no deployed products.
Additional specific APU demonstrations			
Car	PEM	5 kW	Technology development/demonstration by UTC Power
Bus	PEM	16 kW	Technology development/demonstration by Hydrogenics
Garbage Truck	PEM	32 kW	Technology development/demonstration performed by Heliocentris.

There has been considerable interest, development, and demonstration of systems within the recreational vehicle, commercial truck, aviation, and maritime markets. A few limited demonstrations have been made for other applications including a luxury car, bus, and garbage truck. Additional information on the four primary markets and their associated demonstrations is listed below.

Recreational Vehicles

In terms of total number of deployed systems, the RV sector leads the worldwide market in integrating fuel cells into onboard APUs. Over 17,500 fuel cell APUs for RVs have been sold in European markets. These APUs are hybrid systems that integrate a fuel cell stack of 100 W or less with vehicle batteries.

While fuel cell technology has had success in the RV market for APUs in Europe, there are not strong economic or policy drivers for adoption of fuel cells in the U.S. market. Advantages of reduced noise and reduced pollution, compared to IC engine APUs, could lead to increased adoption of fuel cell APUs in the RV market provided costs are comparable.

Commercial Truck

Over half the states in the U.S. maintain some form of anti-idling regulations, leading to an increase in demands for APUs for commercial trucks.[15] More stringent emissions regulations for APUs also will drive the implementation of more efficient technologies for APUs. Typical power requirements for commercial truck APUs range from 1 to 7 kW.

There are approximately 700,000 trucks with sleeper berths currently deployed in the field, creating a significant potential market. A substantial portion of these, estimated at about 2/3 of the population, are long-haul sleeper trucks with an average trip length in excess of 500 miles. Long-haul trucks average approximately 1,456 hours of dicretionary idle operation per year,

[15] American Transportation Research Institute Compendium of Idling Restrictions, January 2012.

mainly to maintain driver comfort levels[16]. The total population of freight trucks is nearly 5.2 million. Day-cab trucks idle for approximately 312 hours per year during loading/unloading queues or rest stops.[17] The higher efficiency of fuel cell technologies offers the potential to reduce operating costs.

The combination of market drivers, market size, and technological readiness make the commercial truck market the most likely near-term application for commercial fuel cell APUs.

Aviation
Aviation is an emerging market for APU applications. In addition to using APUs for ground power, there is interest in using similar systems to reduce peak demands, particularly as future generations of airplanes are expected to have increased electric power demands. There is also interest in using a system similar to an APU as the primary power for Unmanned Aerial Vehicles (UAVs) or small planes. While the APU for ground use would typically range from 100 to 450 kW, an APU to trim in-flight peak demand could be as small as 20kW. UAV power systems can be as small as 3kW.[18]

Maritime
There is market interest in using fuel cell technologies for maritime applications due to the higher efficiency, lower emissions, and quieter operation of fuel cell systems. The potential fuel cell applications range from APUs for recreational and military vessels to primary power systems. The state of market development is very early with a broad selection of fuel cell technologies undergoing evaluation, development, and assessment. While there are a few commercial demonstration projects,[19] the current maritime market is largely driven by military objectives and requirements.

To realize significant and immediate market penetration for commercial truck APUs it is assumed that the commercial truck APU will be fueled by ULSD. The technical targets for Fuel Cell APUs are taken from the DOE Multi-Year Research, Development, and Demonstration (MYRDD) plan and shown in Table 3-4.[20] Note that many of the requirements, including power density and specific power, are competitive with existing products shown in Table 3-2.

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[16] Brodrick C, Brodrick Lipman TE, Farshchi M, Lutsey NP, Dwyer HA, Sperling D. et al. Evaluation of fuel cell auxiliary power units for heavy duty diesel trucks. Transportaion Research Part D 2002;7:303–15.
[17] DOE Hydrogen Program Record #9010, November 3, 2009.
[18] DOD-DOE Aircraft Petroleum Use Reduction Workshop, http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_aircraft_petrol_use.html.
[19] DOE EERE 2010 Fuel Cell Technologies Market Report.
[20] Fuel Cell Technologies Program Multi-Year Research, Development, and Demonstration Plan, http://www1.eere.energy.gov/hydrogenandfuelcells/mypp/

Table 3-4. DOE Technical Targets for APUs Operating on Ultra Low Sulfur Diesel

Characteristic	2011 Status	2013 Target	2015 Target	2020 Target
Electrical efficiency at rated power	25%	30%	35%	40%
Power density	17 W/L	30 W/L	35 W/L	40 W/L
Specific power	20 W/kg	35 W/kg	40 W/kg	45 W/kg
Factory Cost, stack + required balance of plant (50,000 units annually, 5kW)	$750/kW	$700/kW	$600/kW	$500/kW
Factory cost, system (50,000 units annually, 5kW)	$2,000/kW	$1,400/kW	$1,200/kW	$1,000/kW
Transient response (10 to 90% rated power)	5 min	4 min	3 min	2 min
Startup time from: 20°C Standby conditions	 50 min 50 min	 45 min 20 min	 45 min 10 min	 30 min 5 min
Degradation with cycling	2.6%/1,000 h	2%/1,000 h	1.3%/1,000 h	1%/1,000 h
Operating lifetime (time until >20% net power degradation)	3,000 h	10,000 h	15,000 h	20,000 h
System availability (excluding scheduled maintenance)	97%	97.5%	98%	99%

Additional requirements specified in the MYRDD include:

- The degradation requirement in Table 4 is expected to include daily cycles to standby condition and weekly cycles to full off condition (ambient temperature)
- The system should meet durability criteria after exposure to vibration typical of transportation and highway operation
- Ambient temperature range of -40 to 50°C
- Ambient relative humidity range from 5% to 100%
- Ambient dust levels up to 2 mg/m^3

Assuming ULSD is the supply fuel, the higher tolerance to impurities of SOFC and HTPEM technologies gives them a considerable advantage over 80°C PEM technologies. The higher power to mass ratio associated with SOFC technologies offers an advantage relative to HTPEM. However, SOFC technologies will have a longer startup time. A HTPEM stack is capable of a more rapid startup, although this is somewhat tempered by the startup time of the associated reforming system.

3.2 APU Technology Selection

Battelle started with the entire range of systems sizes and technologies specified in the funding announcement DOE FOA-0000420. A matrix of possible systems was constructed using the system (size and fuel cell type) as columns and the specific APU application as rows. From this matrix, individual systems were removed from consideration in FY12 based upon typical market applications, state of technology development, or basic economic arguments. These reasons are identified with letters in Table 3-5 and explained in detail below the table.

Some of the main outcomes of research being funded by DOE are technological advancement and reduced cost. Therefore, it will be worthwhile to reconsider the selection matrix in future years incorporating technological advances as well as lessons learned during prior years. Even though the commercial truck market is identified as the nearest market, consideration for other applications is included in Table 3-5 to facilitate reconsideration in future years.

Table 3-5. APU Application Matrix

Technology		PEM	HTPEM	SOFC	PEM	HTPEM	SOFC	PEM	HTPEM	SOFC	PEM	HTPEM	SOFC	PEM	HTPEM	SOFC	PEM	HTPEM	SOFC
System Size		1 kW			5 kW			10 kW			25 kW			100 kW			250 kW		
APU Application	RV	B	B	B	B	B	B	A	A	A	A	A	A	A	A	A	A	A	A
	Commercial Truck	C	H	12	C	H	12	D	D	D	D	D	D	D	D	D	D	D	D
	Maritime	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E	E
	Commercial Aviation	F	F	F	F	F	F	G	G	G	G	G	G	G	G	G	G	G	G

Considered in FY12-FY13

Technology Selection Criteria and Notes

A. Based upon Battelle's market research conducted in support of this project, fuel cell system sizes above 5 kW are not required to meet typical loads in RVs.

B. The advantages of fuel cell technology, particularly reduced noise, would be beneficial to the RV user. There is not a strong regulatory or financial market driver for fuel cell APUs for this application. We suggest that consideration of 1 and 5 kW systems for RV APUs be deferred until APU costs for similar sizes in other APU markets are developed. This will enable a general assessment of the cost competitiveness of fuel cell APUs for the RV market and determine if additional refinement of the APU cost model is beneficial.

C. A lack of hydrogen infrastructure means that the near-term applications for commercial truck APUs will most likely use reformate from ULSD for fuel. The additional cost, weight, and volume of equipment required to purify hydrogen to the requirements for a standard temperature PEM stack make this technology less attractive.

   The selection should be revisited once comparative costs for a Material Handling Equipment 1 kW and 5 kW fuel cell systems based on PEM technology are developed.[21] If the PEM approach offers significant advantages with respect to cost or size, it may be worth considering an APU based on PEM technology that includes the ULSD reforming and purification equipment.

D. OEM load profiles indicate typical loads expected for Class 8 sleeper trucks are from 2.5 kW to 4.0 kW.[22] An APU of 1 kW nominal size may be paired with batteries to meet peak demands.[23] Fuel cell systems of 10 kW and more are oversized for present and forecasted loads.

E. APUs for maritime applications were a focus of a DOE workshop in May 2011.[24] The current state of technology development is proof-of-concept demonstrations. The demonstration systems

[21] These analyses are planned for FY13 of the current project.

[22] Hennessy, D., Solid Oxide Fuel Cell Development for Auxiliary Power in Heavy Duty Vehicle Applications, 2010 DOE Annual Merit Review.

[23] Norrick, D., Diesel Fueled SOFC System for Class 7/Class 8 On-Highway Truck Auxiliary Power, 2010 DOE Annual Merit Review.

[24] DOE-DOD Shipboard APU Workshop, http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_shipboard_apu.html.

discussed in the DOE workshop generally had power levels of 400 kW and above. Applications ranging from 10kW and higher are potentially applicable to leisure and smaller vessels.[25]

The state of development of market requirements and drivers for maritime APUs under 200 kW is very early. These applications should be revisited in future years of the project when the market requirements and drivers are more clearly defined and understood.

F. Aviation applications for fuel cell powered APUs were a focus of a DOE workshop in September 2010.[26] As with maritime applications, the market is very early. While the benefits of fuel cell technology (reduced emissions, better fuel economy) are clear, the optimum implementation within both present and future aircraft isn't clear. Systems as small as 10 kW have been evaluated for overall performance and ability to reduce peak loads.[27] Existing aviation APUs for commercial aircraft range from 50 to 450 kW.[28] Systems as large as 550 kW may be required, although near-term implementations sized around 100 kW are more likely.[29]

G. Fuel cell technology development has focused on performance, durability, and reliability improvements beneficial to several market applications. The aviation market will require these to continue to advance, as well as focused development to improve performance relative to requirements specific to aviation applications including operation at altitude, tolerance for higher levels of shock and vibration, and improvements to specific power (power per unit weight). A significant gap exists between the current state of technology development and the market requirement for specific power.

   While there is significant interest in the aviation APU market, considerations of this market are best delayed until future years of the project. In addition to meeting all the requirements of a ground application APU, an APU for aviation applications must meet several additional performance requirements. The most stringent of these is the specific power of the system. Current technology is approximately 35 W/kg. While this is approximately in line with DOE targets for the commercial truck APU market,[30] a tenfold increase to the range of 400 W/kg to 500 W/kg is believed to be necessary for the application to be viable in the aviation market.[31]

H. Discussions with industry indicates that SOFC is favored over HTPEM for this application leading to a lack of available information for HTPEM systems.

APU Size and Technology Selected for Analysis

Based on the application requirements of Table 3-3 and the technology selection matrix in Table 3-5 Battelle conducted a cost analysis in FY12 and FY13 of a fuel cell system for APU applications with 1 kW and 5 kW net fuel cell system powers. Annual production volumes of 100, 1,000, 10,000, and 50,000

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[25] Hoffman, D., System Design: Lessons Learned, Generic Concepts, Characteristics & Impacts, 2011 DOE-DOD Shipboard APU Workshop.

[26] DOD-DOE Aircraft Petroleum Use Reduction Workshop, http://www1.eere.energy.gov/hydrogenandfuelcells/wkshp_aircraft_petrol_use.html.

[27] "DOE/Boeing Sponsored Projects in Aviation Fuel Cell Technology at Sandia," 2010 DOD-DOE Aircraft Petroleum Use Reduction Workshop.

[28] Battelle market research conducted in support of this task

[29] Renouard-Vallet, G., Fuel Cells for Aircraft Applications, 2010 Fuel Cell Seminar.

[30] PEMFC R&D at the DOE Fuel Cell Technologies Program, 2010 DOD-DOE Aircraft Petroleum Use Reduction Workshop

[31] Solid Oxide Fuel Cell (SOFC) Technology for Greener Airplanes, 2010 DOD-DOE Aircraft Petroleum Use Reduction Workshop.

units were considered. The market assessment identified SOFC as a fundamentally superior technology. Therefore Battelle proceeded with design of APU systems based on SOFC technology because of its suitability for use with reformed fuels. The full system specifications were determined from consideration of the market requirements and DOE technical targets and include the following:

- Net power output: 1 kW and 5 kW
- Input fuel: ULSD meeting EPA requirements
- Operating lifetime: 10,000 hrs (2013 Target)
- Degradation with cycling: 2%/1,000 hr (2013 Target)
- Electrical efficiency at rated power: 30% (2013 Target)
- System availability: 97.5%
- Operational load: capable of meeting typical truck APU duty cycle

Additional targets including transient response, power density, specific power, and startup time were system design parameters. A system design suitable for cost analysis should contain enough detail to accurately determine these metrics.

There is clear market interest and recognition of the advantages of fuel cell APUs for several RV, aviation, and maritime applications. However, in the absence of regulatory or significant financial incentives and faced with significant codes and standards barrier requirements in aviation and maritime applications, these markets are unlikely to develop until fuel cell technology matures further. In future years of this project, the technology selection matrix will be revisited to assess changes in market definitions and conditions or product development that may affect the near-term feasibility of fuel cell systems for other APU applications.

The next step of the project was to take the baseline application requirements for commercial truck APUs and develop example fuel cell system designs that met those requirements. The design effort began with a literature review followed by interviews with product and component developers to assess the current state of technological development and approach as well as identify likely near-term improvements.

4 System Design

To perform a meaningful cost analysis requires that the analysis be applied to a system design that is representative of deployed or likely to be deployed systems. The system design chosen for analysis is necessarily only a strawman for consideration since each fuel cell APU manufacturer will bring to bear their specific approaches to system design, control, and operation. Further, some manufacturers will emphasize cost, others efficiency, still others perhaps noise or other secondary features that they perceive as market discriminators. At this point no fuel cell APU systems are commercially available. Therefore, we have created an example system representing our understanding and synthesis of conversations with possible APU providers. The basic system specifications are based on currently available non-fuel-cell APU systems in the market.

4.1 General System Description

Based on the market analysis results above, Battelle considered 1 kW and 5 kW (net) fuel cell power systems for APUs. The 5 kW example system design focuses on sleeper cabin power for standard Class VIII long haul trucks. The APU serves to reduce truck idling time by providing auxiliary power for heating, air conditioning (A/C) and accessories while the truck is stopped. The 5kW design supplies all necessary power for standard cabin loads. It would interact with the truck primary battery for surge management but would carry the full power of the sleeper cab and be responsible for managing the intermittent loads applied. The 1 kW fuel cell system would likely be hybridized with additional deep cycle batteries and the vehicle's primary battery to provide the necessary power to accommodate the load demand profile while maintaining the batteries at a high state of charge. The 1 kW approach would provide average power for the truck but would depend on batteries to manage a greater percentage of the intermittent loads (e.g. air conditioning). The 1 kW system may be more appropriate for short-run and local delivery trucks than Over-the-Road (OTR) sleepers.

The conceptual APU system integrates a high temperature SOFC with a customized fuel processor that converts the diesel fuel from the truck's onboard tanks into a fuel cell quality reformate. Both the 1 kW and 5 kW systems assume that the SOFC stack will require reformate with less than 0.1 ppmv residual sulfur (as H_2S). For ULSD, this level is below what would generally be expected after reforming so sulfur removal is assumed to be necessary. Development of stacks tolerant to 10 ppm or greater sulfur, as has been reported in some recent RFPs from the military, would enable elimination of this component. Since not all stacks are sulfur tolerant, we have retained it in the analysis. We selected autothermal reforming (ATR) as the most common approach for SOFC systems operating on diesel or similar fuels. In our survey of potential fuel cell integrators, some companies reported using anode gas recirculation to provide water for the ATR, typically using the reformer in catalytic partial oxidation (CPOx) mode for initial heat up, thus eliminating a start-up burner. These approaches are apparently not widely accepted by the industry at large, at least not yet, so they were not included in the strawman system design but are considered as alternatives in our discussion of the cost implications.

Figure 4-1 is a schematic of the system developed for analysis. Fuel is combined with regulated flows of steam and air at the entrance to the reformer. As shown, the reformer is operated at a net exothermic condition so that the outlet temperature is elevated. Energy is recovered from the reformer outlet to vaporizer and superheat the inlet water and preheat the inlet air. The reformate is cooled to approximately 400°C for desulfurization by a zinc oxide bed and then reheated by an anode afterburner before entering the stack. Alternatives to this configuration could include a variety of permeations in the heat management approach such as preheating of the combustion air by the anode afterburner. Most of these reconfigurations would incorporate similar hardware and therefore the cost analysis of this configuration provides a reasonable estimate and helps elucidate the most important cost drivers. Additional detail on this system is included below.

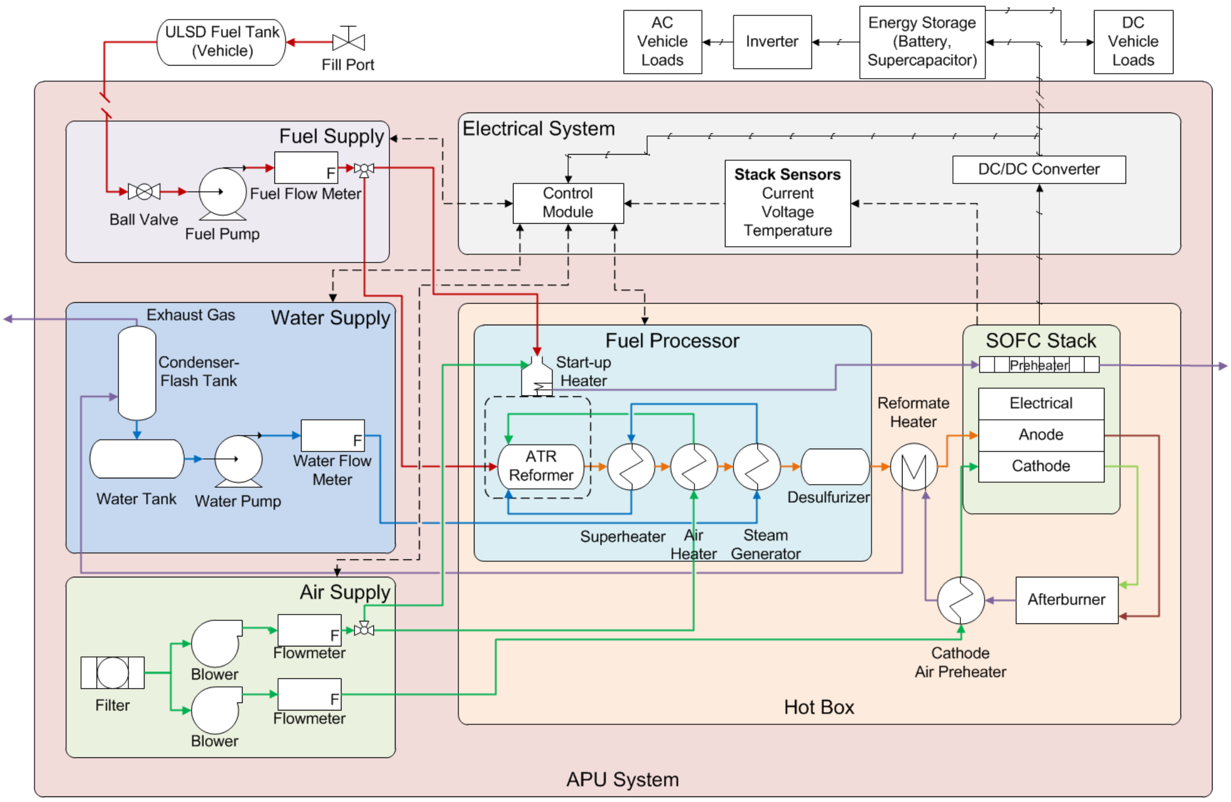

Figure 4-1. SOFC System Schematic for 1 kW and 5 kW APU Applications

In the configuration shown in Figure 4-1, diesel fuel from the vehicle fuel supply is fed to an ATR which processes the liquid hydrocarbons into usable hydrogen, carbon monoxide and methane reformate stream. The reformate is desulfurized to <1ppm sulfur content before going to the SOFC stack to generate electricity. Residual chemical and thermal energy in the reformate leaving the fuel cell is captured in an afterburner to provide air preheating. Additional information on the unit operations shown in Figure 4-1 is provided below.

4.1.1 Reforming Process

For this discussion, the reforming process can be considered as the disassembly of a complex hydrocarbon molecule to release hydrogen and convert the carbon to CO by oxidation. If the oxidant is air, then reforming is accomplished by partial oxidation. Without the presence of a selective catalyst, partial oxidation generally results in significant water formation as well as CO, CO_2, and frequently solid carbon. Hence most partial oxidation reforming is catalytic partial oxidation (CPOx). Partial oxidation is exothermic resulting in a significant increase in reactant temperature. The other main class of reforming is steam reforming (SR, sometimes in the literature as SMR, or steam methane reforming) where the oxygen to oxidize the carbon comes from water. This process is highly endothermic but also releases the hydrogen from the water as well as from the fuel, which can be beneficial. The heat for steam reforming must be supplied from combustion of fuel or, more commonly, by combustion of anode effluent in an afterburner. The need to balance the available heat in the anode with the required heat in the reformer creates some control timing difficulty so this approach is usually only practiced where system efficiency must be maximized. The most common reforming applied to SOFC is a combination of CPOx and SR, nominallyATR. For ATR, both air and steam are supplied to the reactor with the fuel. The balance between air and steam is adjusted to provide a desired net energy release (more air, more CPOx, more energy released). Although it is possible to operate ATR at near net zero energy release, it is common to control air input to control reformer outlet temperature to a level which is compatible with the remainder of the system. We assume the ATR is operated with a slight net energy release for our stawman system so that the reformate is hotter than the reactants. ATR provides rapid response to changes in system load and is typically less prone to carbon deposition than either CPOx or SR alone.

4.1.2 System Operation

Start-up of the strawman system is accomplished by an external burner operating on ULSD. Hot gas from the burner is routed through (or around) the reformer and through (or around) the stack to preheat both. Stack preheating must be carefully managed to avoid excessive thermal stress, hence, the start-up burner must have a relatively wide turndown and the ability to operate with high excess air to manage the hot gas temperature ramp. Once the ATR reactor is sufficiently hot and steam is available, fuel may be diverted from the start-up burner to the ATR reformer. Depending on system specifics, the start-up burner may prefer to remain in operation for stack heating. For our analysis we assumed the start-up burner would not be used at the same time as the reformer so only one fuel pump and one flow meter are required. Once the reformer reaches approximately 400°C the catalyst can begin to convert the ULSD fuel into reformate – though initially the reformate may have relatively low hydrogen and CO as the focus is on stack preheating to approximately 500 to 600°C, the temperature at which the stack may begin to produce some power. During the heat-up of the reformer and stack, cathode air is also being passively heated by the stack effluent. Once reforming is started, additional heat is applied to the cathode air inlet through combustion of the anode effluent. Cathode inlet air temperatures are usually managed to control stack temperature as cathode cooling can be an important factor in stack management.

Once the reformer and stack are up to initial starting temperature, fuel, air, and steam are adjusted to ramp temperature and bring the fuel cell on line. As shown in Figure 4-1, water is vaporized and superheated by the hot reformate gas from the reformer. Air input to the ATR reactor is also preheated by reformate. This heat exchange process cools the reformate to approximately 400°C prior to entering the desulfurization module. The incoming liquid fuel may also be heated to assist in vaporization as the fuel is injected into the reformer volume; however, heating ULSD can result in cracking and coke deposition so the fuel is preferably injected into the steam/air stream through an atomizing nozzle or similar device.

Sulfur in the fuel is converted primarily to H_2S in the reformer. The desulfurizer (a zinc oxide bed) scrubs the H_2S from the reformate stream yielding zinc sulfide as a disposable product. Because the sulfur in ULSD is less than 15 ppm by law, the zinc oxide bed is sized to provide a few thousand hours of operation before replacement.

Typical SOFC stacks do not use 100% of the chemical energy in the reformate as doing so would result in highly non-uniform heat generation in the stack yielding thermal stress problems and requiring a much larger stack. Typical chemical energy utilization seems to be of the order of 50 to 80% depending on system configuration and reforming requirements yielding an anode effluent with significant chemical energy. Partially depleted (and diluted by water), the anode effluent is combusted with additional air in an afterburner. In the strawman system, the afterburner reheats the reformate from the desulfurization reactor to approximately 700°C, a reasonable inlet temperature for the stack. Virtually all of the hydrogen that comes in with the fuel is converted to water in the stack and afterburner. The afterburner gases are condensed to yield the water required for ATR so that no net water is required to be added. As noted below, some systems use anode gas recirculation to the inlet of the ATR reactor to supply the water rather than the condense and re-vaporize approach used here. Accomplishing the recirculation requires a variable speed high temperature blower capable of overcoming the system pressure drop and regulating the return gas as needed for system control. Anode recirculation systems must also manage the net output from the system and maintain appropriate differential pressure across the delicate ceramic components in the stack. In the absence of a well-defined anode recirculation system design and available standard components, this approach was considered too difficult to analyze with confidence.

Overall the system schematic shown in Figure 4-1 remains the same for 1 kW and 5 kW systems. Many of the physical components need to be scaled up to accommodate the larger 5 kW system, but the general layout remains the same. Sizing accommodations were made appropriately for the mechanical, electrical, and computer components when costing both systems. Table 4-1 provides a summary of specifications by component function; Table 4-2 provides details on the fuel cell design. Tables 4-1 and 4-2 are based on our judgment regarding typical and representative specifications and requirements: they are not based on any specific system nor so they constitute recommendations for specific hardware.

Table 4-1. Specifications by Component Function

	1 kW	5 kW
Fuel Supply	• 7 cc/min • 40 psig delivery pressure • Filter to 2 microns	• 34 cc/min • 40 psig delivery pressure • Filter to 2 microns
Water Supply	• 15 cc/min • 40 psig delivery pressure • Filter to 2 microns	• 74 cc/min • 40 psig delivery pressure • Filter to 2 microns
Air Supply	• 23 SLPM Air - Anode • 54 SLPM Air - Cathode • 1 psig minimum outlet pressure at full load	• 117 SLPM Air - Anode • 270 SLPM Air - Cathode • 1 psig minimum outlet pressure at full load
ATR Reformer	• 1 psig operating pressure • Up to 800°C outlet temperature • Reformate throughput 44 SLPM (1 kW) and 218 SLPM (5 kW)	
Desulfurization Reactor	3000 hour capacity at 15 ppmw fuel sulfur content	
Water	• 300°C rated	

<table>
<tr><th></th><th>1 kW</th><th>5 kW</th></tr>
<tr><td>Vaporizer</td><td colspan="2">• <15 psid water side, < 5 inH_2O air side
• 77W heat duty (1 kW), 385W heat duty (5 kW)</td></tr>
<tr><td>Air preheater (Cathode)</td><td colspan="2">• 750°C rated
• < 10 inH_2O pressure drop both sides
• 77W heat duty (1 kW), 385W heat duty (5 kW)</td></tr>
<tr><td>Air Preheater (ATR)</td><td colspan="2">• 700°C rated
• < 10 inH_2O pressure drop both sides
• 187W heat duty (1 kW), 936W heat duty (5 kW)</td></tr>
<tr><td>Steam Superheater</td><td colspan="2">• 400°C rated
• < 15 psid on steam side, 5 inH_2O on air side
• 261W heat duty (1 kW), 1303W heat duty (5 kW)</td></tr>
<tr><td>Start-up Burner</td><td colspan="2">• ULSD burner
• 10:1 turndown
• Output temperature controllable from 400 to 1000 °C</td></tr>
<tr><td>Anode Afterburner</td><td colspan="2">• 800°C inlet gas and air
• Low BTU anode exhaust gas as fuel</td></tr>
<tr><td>Power Electronics</td><td>• 12 VDC output
• 15 to 21 VDC input
• 2 kW rating</td><td>• 12 VDC output
• 30 to 42 VDC input
• 7 kW rating</td></tr>
<tr><td>Controls</td><td colspan="2">• CANbus[32] interconnected
• Separate Stack and fuel-processor/BOP control modules,
• Custom I/O and processing
• Custom sensor input and device driver output</td></tr>
<tr><td>System Connection</td><td colspan="2">• Mechanical contactor disconnect
• 5/16 inch threaded terminals for 00 gage wiring
• Command input via CANbus</td></tr>
</table>

Table 4-2. Fuel Cell Design Parameters

<table>
<tr><th>Parameter</th><th>1 kW</th><th>5 kW</th></tr>
<tr><td>Cell Power Density (W/cm^2)</td><td colspan="2">0.32</td></tr>
<tr><td>Cell Current Density (A/cm^2)</td><td colspan="2">0.4</td></tr>
<tr><td>Cell Voltage (VDC)</td><td colspan="2">0.8</td></tr>
<tr><td>Active Area Per Cell (cm^2)</td><td>200</td><td>400</td></tr>
<tr><td>Rated Net Power (kW, continuous)</td><td>1</td><td>5</td></tr>
<tr><td>Rated Gross Power (kW, continuous)</td><td>1.22</td><td>6.08</td></tr>
</table>

[32] CANbus: standard automotive digital communication protocol for electronic devices, http://en.wikipedia.org/wiki/CAN_bus

Parameter	1 kW	5 kW
Number of Cells (#)	19	38
Open Circuit Voltage (VDC)	21	42
Full Load Stack Voltage (VDC)	15.2	30.4
Cell Design	Planar, Anode supported	
Anode Material	Ni-8YSZ, 250 μm thick	
Anode Application	Tape cast, kiln fired	
Anode Active Layer Material	NI-YSZ, 15 μm thick	
Anode Active Layer Application	Screen Print, kiln fire	
Anode Contact Layer Material	NI-YSZ, 10 μm thick	
Anode Contact Layer Application	Screen Print, kiln fire	
Electrolyte Material	8YSZ, 8 μm thick	
Electrolyte Application	Screen print, kiln fire	
Cathode Active Layer Material	YSZ/LSM, 5μm thick	
Cathode Active Layer Application	Screen Print, kiln fire	
Cathode Material	LSCF, 30 μm thick	
Cathode Application	Screen Print, kiln fire	
Cathode Contact Layer Material	LSM/YSZ, 10 μm thick	
Cathode Contact Layer Application	Screen Print, kiln fire	
Seals	Wet application bonded glass/ceramic	
Stack Assembly	Hand Assembled, tie rods, furnace brazed	
Interconnects	Ferritic Stainless Steel (SS-441) with Perovskite coating, 2-3 μm thick	
End Plates	A560 Cast Steel	

4.2 Electrical System

The assumed electrical topology shown in Figure 4-1 is just one of many design possibilities. This topology was selected based on industry feedback and general knowledge of the components and the application. The primary role of the electrical system is to manage the transfer of power to the load. The components of this system are sized with the assumption that the fuel cell provides the nominal power consumed by the equipment and any power required to recharge the battery while the battery provides any surge power required in excess of the nominal power, for example compressor starting inrush current. These periods of excess power or peak loads were assumed to be no more than 3 times the maximum output power of the fuel cell for ten seconds or less. The following sections provide more detail on each of the major components in the electrical system.

Output voltage from the fuel cell depends on number of cells and the load. Fuel cells exhibit a greater change in output voltage with load than do batteries. Therefore, specialized power converters are usually needed to interface the stack with batteries (or other storage). For some specialized applications the fuel cell may be configured to connect directly to some loads (usually motors); however, for most applications a DC/DC converter will be required. In a fuel cell system that includes a reformer, the DC/DC converter also manages allowed power draw to prevent damage to the stack.

In addition to the DC/DC converter, electrical equipment includes controls, sensors, and the power and signal/sensor cables interconnecting the system components. Generally the sensors and cabling will be automotive type with minor customization. The controllers will be similar to automotive computers though may require different I/O characteristics and are therefore assumed to be similar to automotive but with some customization for the cost analysis.

4.2.1 DC/DC Converters

The high power DC/DC converter is located between the fuel cell and the battery. The converter converts the varying output voltage of the stack to the managed (but not necessarily constant) voltage required by the energy storage system. In a fuel cell system using a reformer, the converter is responsible for communicating load to the system controls as well as to limiting in response to system conditions if required.

The converter chosen for this analysis is a step-down (buck) converter. This converter topology was selected because it is well defined, consists of minimal components, and can be very efficient at high power levels. For this topology to work properly, the fuel cell output voltage at full load must be higher than the nominal operating voltage of the batteries, in this case 12V. The buck circuit configuration assumed is non-isolated. High current levels are often achieved via placing multiple buck modules in parallel; however, single modules that provide all the current are also an option. Both were used for cost comparison.

A smaller DC/DC converter (not shown in Figure 4-1) is used to power to the control electronics and miscellaneous support equipment in the system. This converter generates a lower, more tightly regulated voltage from the 12 V power bus for the electronics in the system.

4.2.2 Control and Sensors

A system controller is required to manage the subcomponents of the fuel cell system to provide the appropriate output power and maintain thermal balance and stability of the system by managing fuel, water, and air flows. Depending on system designer preference and specific system configuration, individual controllers may be used for each subsystem (distributed control) or a single control board may accept all sensor inputs and provide all control outputs. For this cost analysis we assume a single controller will be used. Since the subassemblies are likely in close proximity and tightly packaged for minimum volume, the space overhead required for distributed controls is not desirable.

4.2.3 Protective Devices

The protective components are intended to prevent catastrophic failures and to protect the user. Unlike compressed hydrogen systems, an ATR/SOFC system does not involve high pressure. However, the system does include high temperatures and high currents along with a potential for leaking gas containing hydrogen (easily ignited) and CO and H_2S (poisons). Therefore, most systems include combustible gas monitors. Certain components may have internal protection devices such as current limiting features on the output of the DC/DC converter. A contactor isolates the fuel cell output when the system is not in use or in the event of a system trip because the output voltage of the fuel cell is higher than the recommend maximum safe DC touch voltage (5 kW system). All high current wiring regardless of voltage should be provided with terminal protection.

4.2.4 Connector and Cabling

The connectors and cables that complete all the interconnections between electrical components in the system must be rated for the environment in which the equipment is to be used. As a result automotive style water resistance connectors are used in this design. The wire and cable is assumed to be of the same quality as those used in the automotive industry as well. However, reformer and stack sensors require high temperature wire and insulation or other forms of thermal isolation which are not typical of automotive applications.

4.2.5 Alternative Electrical Systems

Alternative electrical system designs exist that seek to simplify or reduce the component cost in the system by removing the DC/DC converter and directly connecting the fuel cell to the batteries. This approach eliminates the cost of the converter at the potential expense of more complicated battery management electronics, additional electronics to manage power flow, and possibly a more involved stack design.

In general, APU designs are constrained by volume and weight available under the cab of the tractor. If the cab were configured to incorporate an APU, additional alterations and improvements would become feasible

4.3 Balance of Plant (BOP)

4.3.1 System Layout

The 1 kW and 5 kW APU systems share the same general layout and nominal parts list. Standard Original Equipment Manufacturer (OEM) items are used where possible for all electrical management and fuel delivery. Otherwise, high temperature and fuel conversion equipment is specified based on industry development trends and stakeholder feedback.

4.3.2 Anode Gas Recirculation Consideration

Feedback from industry stakeholders indicates that a more efficient method of capturing product waste heat and water may be Anode Gas Recirculation (AGR); whereby a portion of anode exhaust from the stack is recirculated directly back to the reformer. This method allows the reclamation of water without condensation, reclamation of heat without a heat exchanger and use of residual anode chemical energy (H2 and CO) without a burner. Although there is significant data for AGR in Steam Methane Reforming or CPOX[33], we did not identify sufficient literature to support an AGR design for diesel ATR. Therefore, the system outlined above uses excess cathode air to combust the remaining fuel in the anode exhaust which then provides heat to incoming gas streams and condensate for the ATR water balance.

[33] D Shekhawat, DA Berry, TH Gardner, DL Haynes, JJ Spivey, Effects of fuel cell anode recycle on catalytic fuel reforming. Journal of Power Sources 168 (2007) 477-483

Additionally, due to the high temperature requirements for all equipment in the gas stream, an AGR blower would drive up the cost of BOP significantly.

4.3.3 Heat Exchangers

The system schematic in Figure 4-1 includes five specialty heat exchangers. As noted in Table 4-1, these heat exchangers are expected to operate with temperatures as high as 800°C (potentially higher during transient and upset conditions). Low pressure drop is an important design feature for all heat exchangers, though the water vaporizer and steam superheater may accommodate significant pressure drop on the water side if necessary.

Because of the small scale and high temperature requirements, commercially available heat exchangers were not available in the required materials or were overdesigned, oversized, and overpriced for the application. To provide a basis for DFMA™ analysis we assumed the heat exchangers would be fabricated from corrugated thin gage 310SS stock and high-temperature furnace brazed or laser welded to yield sealed assemblies. In early production, the heat exchangers are likely to be identical and sized for the highest heat duty. This choice enables single SKU component stocking and allows tooling and set-up costs to be spread over a greater number of parts. As system designs mature and product sales volumes develop, specialization and design-to-purpose will bring down costs as well as decrease overall system size. In the absence of a more detailed design, we did not include benefits of specialization except though the "learning curve" factor.

4.3.4 Fuel Delivery and Management

The fuel delivery system is based on research of various liquid fuel management systems and follows methods being developed by Argonne National Laboratory, which integrates standard OEM diesel fuel injectors to inject and mix liquid fuel droplets into the inlet stream of the reforming reactor[34]. Automotive (diesel and/or gasoline) meet requirements similar to those for our system. Diesel engine fuel injectors are designed to generate extremely small droplets (necessary for rapid evaporation in cylinder, desirable for ATR), but require a high pressure (expensive pump, significant parasitic power for small systems); alternatively, gasoline injectors do not require high pressure, but yield larger droplets. Based on the high temperature and lower pressure requirements, slightly reduced diesel injector costs were used in pricing the system.

4.3.5 Reformer Design

The reformer design is similar to the Three Way Catalyst (TWC) reactor (catalytic converter) found on automobiles. The reactor portion is composed of a catalyst coated ceramic monolith to maximize surface area and residence time without creating a significant pressure drop. The coated monolith is structurally supported by a refractory fiber mat to ensure adequate compression, thermal expansion tolerance, and seal gaps around the reactor during heat-up and cool-down. Upstream is a high porosity alumina foam segment to assist mixing of the heated fuel, air, and steam prior to the monolith.

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[34] D Liu, S Sheen, M Krumpelt, Diesel Reforming for Solid Oxide Fuel Cell Applications. Presentation at SECA Core Technology Peer Review Workshop, Tampla FL, 2005

4.3.6 Catalyst Selection

A noble metal catalyst was selected for this application and preparation was assumed to be comparable to those used for automotive catalytic converters. Cost numbers listed in section 5 for reactor monolith include price of catalyst and coating.

4.3.7 Desulfurizer

The desulfurizer is a modular unit designed as a simple tubular packed bed reactor. The sorbent is zinc oxide in the form of pellets.

4.3.8 Method of Costing

The system specifications were used to derive the requirements for specific BOP components. Suitable components that met these requirements were identified from multiple manufacturers. The associated costs were then obtained by soliciting quotes or price estimates from a minimum of three manufacturers when possible. The multiple quotes were then compared to develop a generic cost. However, three quotes could not be obtained in some instances, such as when a unique component was produced by one, widely accepted manufacturer or if the component was not a commercially available part.

Many BOP components are readily available and costing could be estimated at the larger volumes of 1,000 and 10,000 units. For those few items that are currently not being produced at large quantities, a vendor either provided budgetary pricing or a suitable discount was assumed for mass production. This was often the case for fuel conversion and high temperature components.

Four main components that are not readily available commercial items are the ATR fuel reformer, high temperature heat exchangers, desulfurizer and start-up burner. All four items were priced using the DFMA™ software with manufacturing methods estimated by combining Battelle's general experience, end-user feedback, and similar products from original equipment manufacturer (OEM) or aftermarket automobile parts. Similarly, no suitable COTS item was identified for the cathode flow meter and fuel delivery injector. SOFC systems currently on the market use automotive OEM parts that have been proprietarily modified or flow meters that are still undergoing research and development. Consequently, costs for the flow meter were obtained using retail prices for replacement automotive parts and suitable quantity scaling factors. As with the flow meter, the fuel injection system was priced using similar systems for automotive applications.

5 Manufacturing Cost Analysis

Manufacturing cost analysis was applied to custom fabricated components (e.g. fuel cell stack) and to the labor and equipment required for overall assembly of custom fabricated and commercially purchased hardware into a complete system. Key assumptions include:

- Standard manufacturing process apply in most instances for fabricated components. Where specialty manufacturing processes are required industry input was sought to assist with defining the cost parameters
- Manufacturing methods and tooling were customized to the level of production being analyzed.

- Capital equipment and building costs were assumed to be amortized over 20 years,
- Material costs were based on quotes and industry standard assumptions.
- The production methods modeled by a commercially available software package (Boothroyd-Dewhurst DFMA™) are representative of achievable production costs.

Using the Boothroyd-Dewhurst DFMA™ software, component costs calculated from custom and library manufacturing processes were combined with quotes for the outsourced components and incorporated into the assembly and test sequence models to determine the final cost of producing the fuel cell systems. The output of the DFMA™ models was also used to calculate production line utilization leading to a determination of the number of individual process lines required to support various product demand levels. This information was input to the manufacturing capital cost model. Capital equipment expenditures for production were amortized over a 20-year period and the annual amortized cost was distributed over the production volume for that year. The financial assumptions used are consistent with the DOE Hydrogen Analysis (H2A) model. Total fuel cell APU system costs including capital expenditures were then estimated for the baseline system and projected improvements.

The sections below address the fabrication and manufactured cost estimation of key custom components in sufficient detail to allow evaluation of the primary cost drivers. Research supported by DOE under the SECA core program has already influenced the stack manufacturing cost distribution with significant cost savings being achieved in sealing and cell fabrication methods and materials. These efforts have shifted the internal cost ratios so that the core ceramic cell technology may no longer be the most expensive subcomponent. Following the stack manufacturing discussion, additional analysis is applied to the reformer, desulfurizer, and other components leading to an overall cost estimate.

5.1 Stack Manufacturing Process and Cost Assumptions

The SOFC fuel cell stack consists of end plates, interconnects, picture frames, ceramic anode/electrolyte/cathode cells, and glass-ceramic sealant as shown in Figure 5-1. General stack production process cost assumptions are presented in Table 5-1 below. Refer to Appendix A for details of the analysis.

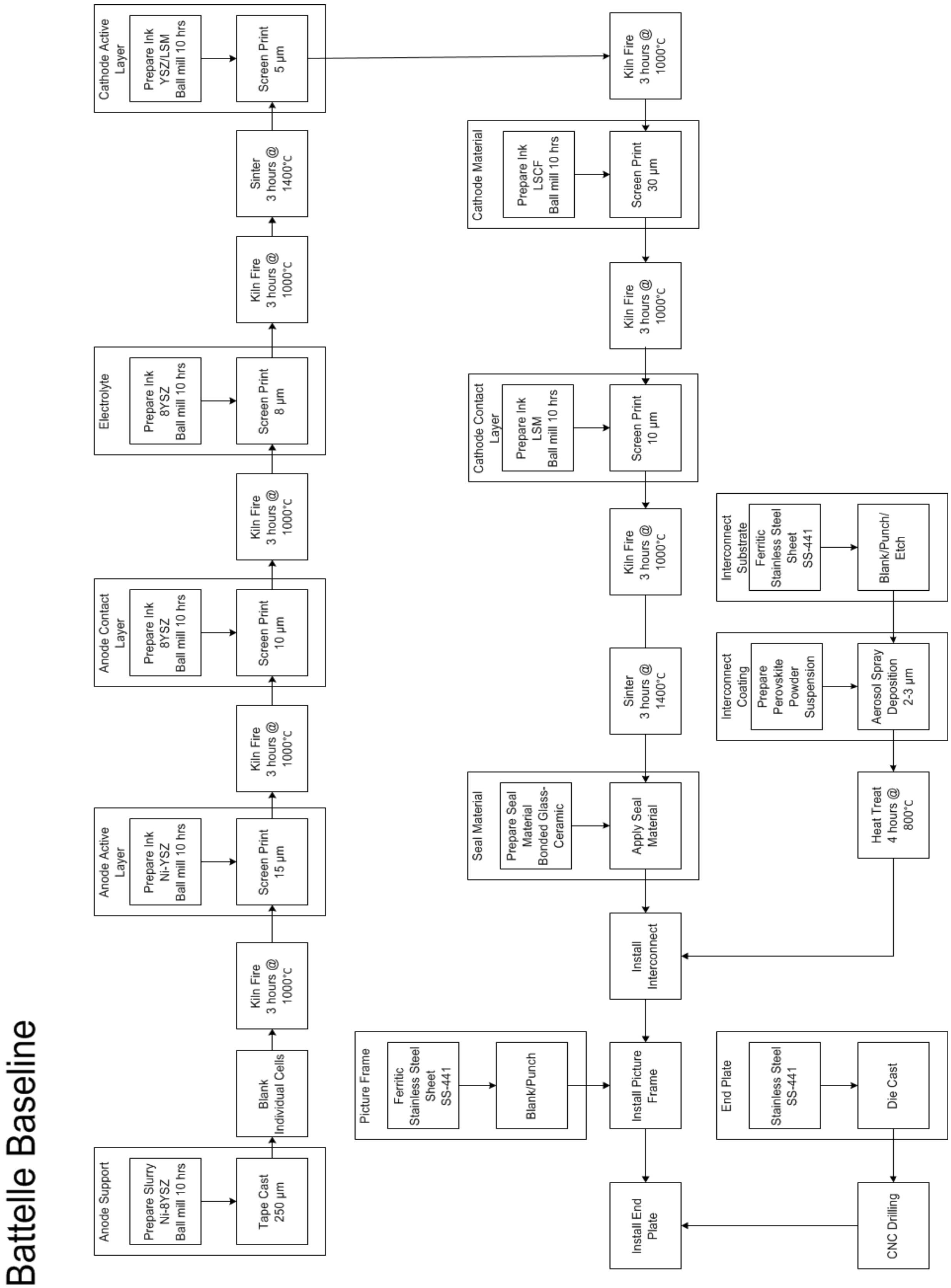


Figure 5-1. Stack Manufacturing Process

Table 5-1. General FC Stack Process Cost Assumptions

Labor cost	\$45.00/hr
Machine cost	\$25.00/hr
Energy cost	\$0.07/kWh
Overall plant efficiency	85.00%

Costs are also influenced by the manufacturing batch size – the number of units assembled during a single production run. For costing purposes, we assumed the following batch sizes based on annual production volumes:

Table 5-2. General FC Stack Batch Size Assumptions

	Batch Frequency	Batch Size
100 stack/year	Semi-annually	50
1,000 stack/year	Quarterly	250
10,000 stack/year	Monthly	840*
50,000 stack/year	Weekly	1000**

* 760 stacks produced in 12th month

** Production occurs over 50 weeks

5.1.1 End Plates

The end plates align with the fuel cell stack across the length of the plate, and overhang the stack width by 30 mm on each side to accommodate the eight tie rods that will press and hold the stack together. The end plate has four reamed and tapped holes for mounting fuel and exhaust gas connectors. The process selected to produce the end plates was die casting A560 stainless steel. The die cast plate is then moved to a Computer Numerically Controlled (CNC) drilling center to drill and ream the eight tie rod holes, and drill, ream and tap the four gas connector holes. For all volumes, the material cost was assumed to be \$5.64/kg, and the process scrap rate was assumed to be 0.5%. The end plate cost summary is provided in Table 5-3.

Table 5-3. End Plate Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	\$13.91	\$13.91	\$13.91	\$13.91	\$23.63	\$23.63	\$23.63	\$23.63
Labor	\$3.19	\$0.32	\$0.13	\$0.13	\$3.85	\$0.39	\$0.15	\$0.15
Machine	\$6.42	\$6.42	\$6.42	\$6.42	\$6.58	\$6.58	\$6.58	\$6.58
Energy	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00	\$0.00
Scrap	\$0.24	\$0.24	\$0.24	\$0.24	\$0.38	\$0.38	\$0.38	\$0.38
Tooling	\$1.05	\$1.05	\$1.05	\$1.05	\$1.50	\$1.50	\$1.50	\$1.50
Part Total	**\$24.81**	**\$21.94**	**\$21.75**	**\$21.75**	**\$35.94**	**\$32.48**	**\$32.24**	**\$32.24**
# per Stack	2	2	2	2	2	2	2	2
Stack Total	\$49.62	\$43.88	\$43.50	\$43.50	\$71.88	\$64.96	\$64.48	\$64.48
Capital Cost	**\$200,000**	**\$200,000**	**\$200,000**	**\$400,000**	**\$200,000**	**\$200,000**	**\$200,000**	**\$400,000**

5.1.2 Interconnects

The interconnects are manufactured from 3 mm thick ferritic stainless steel (SS-441) sheet. The material is stamped into a rectangular blank, then punched to provide the anode and cathode gas path openings. For all volumes, the SS-441 material cost was assumed to be \$5.31/kg, and the process scrap rate for the stamping operation was assumed to be 0.5%. Following stamping, the interconnects are laser etched on both sides to create the anode and cathode lateral gas paths, then spray coated with a perovskite material with a material cost estimated at \$150.00/kg for all volumes. The coated interconnects are heat treated at 1000°C for 4 hours. The interconnect cost summary is provided in Table 5-4.

Table 5-4. Interconnect Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$6.99	$6.99	$6.99	$6.99	$11.91	$11.91	$11.91	$11.91
Labor	$0.87	$0.74	$0.71	$0.71	$1.35	$1.28	$1.27	$1.27
Machine	$0.93	$0.93	$0.93	$0.93	$1.93	$1.93	$1.93	$1.93
Energy	$0.03	$0.03	$0.03	$0.03	$0.07	$0.07	$0.07	$0.07
Scrap	$0.06	$0.06	$0.06	$0.06	$0.10	$0.10	$0.10	$0.10
Tooling	$0.05	$0.05	$0.05	$0.05	$0.06	$0.06	$0.06	$0.06
Part Total	**$8.94**	**$8.80**	**$8.78**	**$8.78**	**$15.42**	**$15.35**	**$15.34**	**$15.34**
# per Stack	19	19	19	19	38	38	38	38
Stack Total	$169.89	$167.26	$166.80	$166.80	$585.91	$583.27	$582.81	$582.81
Capital Cost	**$326,370**	**$326,370**	**$326,370**	**$831,850**	**$326,370**	**$326,370**	**$431,370**	**$2,581.850**

5.1.3 Picture Frame

The picture frames are manufactured from 0.08 mm thick ferritic stainless steel (SS-441) sheet. The material is stamped into a rectangular blank, then punched to provide the anode and cathode gas path openings. For all volumes, the SS-441 material cost was assumed to be $5.31/kg, and the process scrap rate for the stamping operation was assumed to be 0.5%. The picture frame cost summary is provided in Table 5-5.

Table 5-5. Picture Frame Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.16	$0.16	$0.16	$0.16	$0.26	$0.26	$0.26	$0.26
Labor	$0.04	$0.04	$0.04	$0.04	$0.04	$0.14	$0.14	$0.14
Machine	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02	$0.02
Energy	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Scrap	$0.00	$0.00	$0.00	$0.00	$0.00	$0.01	$0.01	$0.01
Tooling	$0.05	$0.05	$0.05	$0.05	$0.05	$0.01	$0.01	$0.01
Part Total	**$0.27**	**$0.27**	**$0.27**	**$0.27**	**$0.37**	**$0.37**	**$0.37**	**$0.37**
# per Stack	19	19	19	19	38	38	38	38
Stack Total	$5.13	$5.13	$5.13	$5.13	$14.06	$14.06	$14.06	$14.06
Capital Cost*	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

*Note: the stamping machine used for the interconnect plates will also be used to create the picture frames, therefore no additional capital cost beyond the specific tooling is incurred for picture frame manufacturing.

5.1.4 Ceramic Cell

The ceramic cell is built up in layers. Each layer starts as an aqueous ceramic slurry that is ball-milled into a uniform suspension. The anode support is created by tape casting and blanking. Subsequent layers are screen printed onto the anode support. All layers are infrared conveyor dried following application, and then kiln fired. The cell is sintered twice, following application of the electrolyte layer, and following application of the final cathode layer. See Appendix A for details of the ceramic cell production process. For all volumes, the scrap rate was assumed to be 3.0%.

Single component ceramic powder material price quotes for lot sizes of 250 kg and 2500 kg were obtained from a domestic supplier, while larger lot size price quotes were obtained from web searches of off-shore suppliers. These prices were analyzed using the learning curve technique detailed in Appendix A.12 to obtain price estimates for various annual material usage rates, as shown in Figure 5-2.

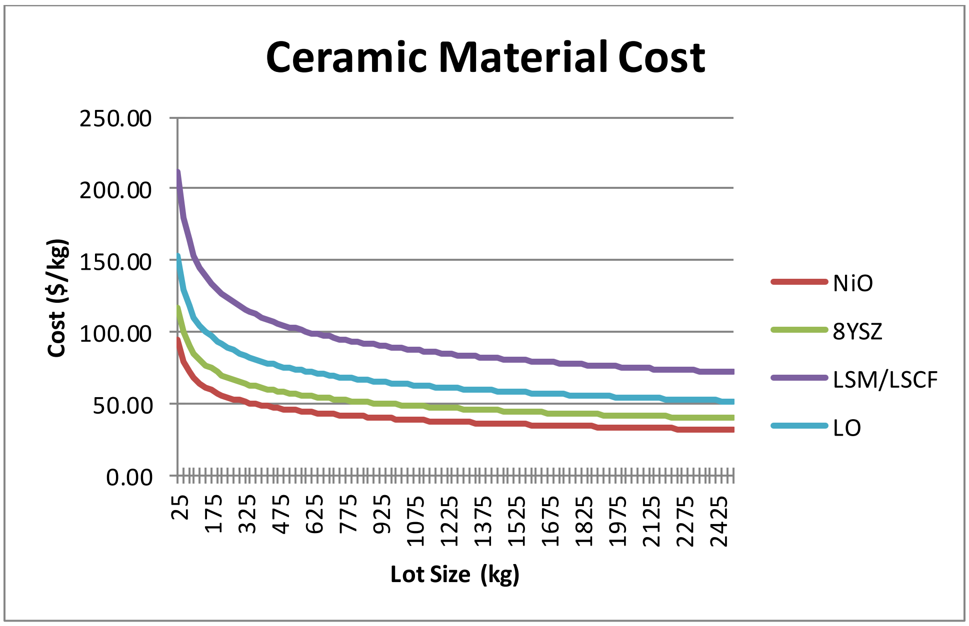


Figure 5-2. Ceramic Material Cost Curves

Annual material usage rates were calculated in accordance with the various slurry manufacturing requirements computed as shown in the models in Appendix A.1, and summarized in

Table 5-6 and Table 5-7.

Table 5-6. 1 kW Stack Annual Material Usage (kg)

Annual Volume	NiO	8YSZ	Ni-YSZ	LSM-YSZ	LSCF	LO
100	32.3	23.9	2.28	1.71	3.61	1.33
1,000	323.0	239.4	22.80	17.10	36.10	13.30
10,000	3,230.0	2,394.0	228.00	171.00	361.00	133.00
50,000	16,150.0	11,970.0	1,140.00	855.00	1,805.00	665.00

Table 5-7. 5 kW Stack Annual Material Usage (kg)

Annual Volume	NiO	8YSZ	Ni-YSZ	LSM-YSZ	LSCF	LO
100	125.4	92.34	12.16	7.22	16.72	3.8
1,000	1,254.0	923.40	121.60	72.20	167.20	38.0
10,000	1,2540.0	9,234.00	1,216.00	722.00	1,672.00	380.0
50,000	62,700.0	46,170.00	6,080.00	3,610.00	8,360.00	1,900.0

The material prices used as inputs to the stack cost models are shown in Table 5-8 and Table 5-9.

Table 5-8. 1 kW Stack Ceramic Cell Material Cost Assumptions

	Annual Volume (stacks)			
	100	1,000	10,000	50,000
Material	Material Cost	Material Cost	Material Cost	Material Cost
NiO	$94.00/kg	$53.00/kg	$30.00/kg	$27.00/kg
8YSZ	$118.00/kg	$70.00/kg	$40.00/kg	$34.00/kg
Ni-YSZ	$106.00/kg	$106.00/kg	$63.00/kg	$43.00/kg
LSM-YSZ	$165.00/kg	$165.00/kg	$108.00/kg	$72.00/kg
LSCF	$212.00/kg	$212.00/kg	$114.00/kg	$78.00/kg
Water	$0.11/kg	$0.11/kg	$0.11/kg	$0.11/kg
Binder	$2.50/kg	$2.50/kg	$2.50/kg	$2.50/kg
Dispersant	$1.27/kg	$1.27/kg	$1.27/kg	$1.27/kg

Table 5-9. 5 kW Stack Ceramic Cell Material Cost Assumptions

	Annual Volume (stacks)			
	100	1,000	10,000	50,000
Material	Material Cost	Material Cost	Material Cost	Material Cost
NiO	$65.00/kg	$38.00/kg	$27.00/kg	$27.00/kg
8YSZ	$91.00/kg	$51.00/kg	$34.00/kg	$34.00/kg
Ni-YSZ	$106.00/kg	$77.00/kg	$43.00/kg	$31.00/kg
LSM-YSZ	$165.00/kg	$140.00/kg	$75.00/kg	$51.00/kg
LSCF	$212.00/kg	$139.00/kg	$79.00/kg	$61.00/kg
Water	$0.11/kg	$0.11/kg	$0.11/kg	$0.11/kg
Binder	$2.50/kg	$2.50/kg	$2.50/kg	$2.50/kg
Dispersant	$1.27/kg	$1.27/kg	$1.27/kg	$1.27/kg

The resulting ceramic cell costs are shown inTable 5-10.

Table 5-10. Ceramic Cell Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$3.85	$2.57	$1.54	$1.30	$6.24	$3.91	$2.63	$2.47
Labor	$3.46	$2.95	$2.87	$2.84	$3.92	$3.68	$3.64	$3.62
Machine	$5.02	$3.29	$2.98	$2.88	$5.19	$4.32	$4.17	$4.12
Energy	$0.15	$0.15	$0.15	$0.15	$0.29	$0.29	$0.29	$0.29
Scrap	$0.37	$0.26	$0.22	$0.21	$0.46	$0.36	$0.31	$0.31
Tooling	$0.08	$0.08	$0.08	$0.08	$0.14	$0.14	$0.14	$0.14
Part Total	$12.94	$9.31	$7.86	$7.47	$16.25	$12.71	$11.19	$10.95
# per Stack	19	19	19	19	38	38	38	38
Stack Total	$245.91	$176.94	$149.31	$142.02	$617.56	$482.89	$425.07	$416.10
Capital Cost	**$823,165**	**$823,165**	**$823,165**	**$1,737,385**	**$823,165**	**$823,165**	**$1,233,850**	**$5,234,030**

5.1.5 Ceramic-Glass Sealing

A ceramic-glass sealant is applied between the cell, picture frame and interconnect prior to assembling onto the stack. The primary components are lanthanum oxide and borosilcate glass in an organic solvent paste. Borosilicate glass was assumed to cost $2.00/kg as a commodity bulk purchase. Lantanum oxide was estimated to cost between $153/kg and $81/kg, depending on usage volume, as shown in Section 5.1.4. The paste is applied as a 0.25 mm bead using a robotic applicator. The scrap rate was assumed to be 3.0%. The sealing cost summary is provided in Table 5-11.

Table 5-11. Ceramic-Glass Sealing Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.06	$0.06	$0.04	$0.03	$0.08	$0.08	$0.04	$0.03
Labor	$0.70	$0.61	$0.60	$0.59	$0.88	$0.83	$0.83	$0.82
Machine	$0.65	$0.65	$0.65	$0.65	$0.91	$0.91	$0.91	$0.91
Energy	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Scrap	$0.04	$0.04	$0.04	$0.04	$0.06	$0.06	$0.06	$0.05
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	$1.45	$1.36	$1.33	$1.31	$1.93	$1.89	$1.84	$1.82
# per Stack	19	19	19	19	38	38	38	38
Stack Total	$27.63	$25.88	$25.24	$24.90	$73.39	$71.64	$69.90	$69.27
Capital Cost	**$12,500**	**$12,500**	**$12,500**	**$50,000**	**$12,500**	**$12,500**	**$25,000**	**$125,000**

5.1.6 Stack Assembly

The stack components are assembled as shown. Pressure is applied to the completed stack using a hydraulic press, and the tie rods are installed to complete the stack assembly. Tie rod costs were assumed to be $40.00 per stack, and gas fittings were assumed to be $34.00 per stack. Base stack assembly costs were assumed to be $10.97 for the 1 kW stack and $18.55 for the 5 kW stack. After applying learning curve analysis, the average stack assembly costs were calculated as shown in Table 5-12.

Table 5-12. Stack Assembly Costs

	1 kW				5 kW			
	100	1000	10,000	50,000	100	1000	10,000	50,000
Assembly Cost	$89.17	$86.12	$85.81	$85.79	$100.74	$95.36	$94.82	$94.77

5.1.7 Stack Brazing

Following assembly, the stack is furnace brazed to cure the ceramic-glass sealant. The scrap rate was assumed to be 0.5%. The stack brazing cost summary is provided in Table 5-13.

Table 5-13. Stack Brazing Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Labor	$1.15	$0.28	$0.13	$0.08	$1.15	$0.29	$0.14	$0.09
Machine	$1.58	$4.71	$4.71	$4.71	$9.67	$13.57	$13.57	$13.56
Energy	$0.17	$0.52	$0.52	$0.52	$1.06	$1.48	$1.48	$1.48
Scrap	$0.09	$0.17	$0.17	$0.16	$0.37	$0.47	$0.47	$0.47
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$2.99**	**$5.68**	**$5.52**	**$5.47**	**$12.24**	**$15.81**	**$15.65**	**$15.60**
# per Stack	1	1	1	1	1	1	1	1
Stack Total	$2.99	$5.68	$5.52	$5.47	$12.24	$15.81	$15.65	$15.60
Capital Cost	**$100,000**	**$100,000**	**$100,000**	**$200,000**	**$100,000**	**$100,000**	**$100,000**	**$400,000**

5.1.8 Stack Testing and Conditioning

Following assembly, the stack is place on a test stand and subjected to a 6 hour test and conditioning cycle to assess its fitness for installation into a system. The cycle consists of a 2 hour warm-up, 2 hours at full power, and a 2 hour cool-down. The test reject rate was assumed to be 5.0%. The stack testing and conditioning summary is provided in Table 5-14.

Table 5-14. Stack Testing and Conditioning Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$1.36	$1.36	$1.36	$1.36	$6.44	$6.44	$6.44	$6.44
Labor	$157.77	$157.77	$157.77	$157.76	$157.77	$157.77	$157.77	$157.76
Machine	$176.47	$176.47	$176.47	$176.47	$176.47	$176.47	$176.47	$176.47
Energy	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Scrap	$17.66	$17.66	$17.66	$17.66	$17.66	$17.66	$17.66	$17.93
Tooling	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00	$0.00
Part Total	**$353.26**	**$353.26**	**$353.26**	**$353.26**	**$358.34**	**$358.34**	**$358.34**	**$358.60**
# per Stack	1	1	1	1	1	1	1	1
Stack Total	$353.26	$353.26	$353.26	$353.26	$358.34	$358.34	$358.34	$358.60
Capital Cost	**$75,000**	**$150,000**	**$900,000**	**$4,425,000**	**$75,000**	**$150,000**	**$900,000**	**$4,425,000**

5.2 Special BOP Manufacturing Cost Assumptions

Certain BOP components that were not found commercially available were designed by Battelle and modeled using DFMA™. These items include the reformer (with start-up burner), desulfurizer, and heat exchangers.

5.2.1 Autothermal Reformer (ATR)

Using the tapered body design detailed in Appendix section A.13 ATR General Design, a cost analysis based on annual volume is summarized in Table 5-15. Manufacturing and assembly parameters used to perform the analysis were as follows:

- Life volume = 100,000 parts
- Labor rate = $45.00/hr
- Machine cost = $25.00/hr
- Overall plant efficiency = 85%

Table 5-15. ATR Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Reformer Can	$145.32	$137.42	$136.61	$136.58	$224.34	$214.28	$210.57	$210.53
Ceramic Materials	$99.00	$87.01	$72.42	$72.42	$323.85	$288.33	$249.55	$249.55
Startup Heater	$204.71	$192.49	$191.26	$191.23	$204.71	$192.49	$191.26	$191.23
Total	**$449.03**	**$416.92**	**$400.29**	**$400.23**	**$752.90**	**$695.10**	**$651.38**	**$651.31**
Capital Cost	**$440,820**	**$440,820**	**$495,820**	**$716,390**	**$440,820**	**$440,820**	**$495,820**	**$716,390**

5.2.2 *Desulfurizer*

Desulfurizer design is detailed in appendix section A.14 Desulfurizer Design. Manufacturing and assembly parameters used to perform the analysis using the Boothroyd-Dewhurst DFMA™ software were as follows:

- Life volume = 100,000 parts
- Labor rate = $45.00/hr
- Machine cost = $25.00/hr
- Overall plant efficiency = 85%

The desulfurizer costs are summarized in Table 5-16.

Table 5-16. Desulfurizer Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Desulfurizer Can	$16.47	$15.93	$15.74	$15.73	$28.20	$27.57	$27.39	$27.37
Zinc Oxide Pellets	$0.35	$0.35	$0.35	$0.35	$1.05	$1.05	$1.05	$1.05
Total	**$16.82**	**$16.28**	**$16.09**	**$16.08**	**$29.25**	**$28.62**	**$28.44**	**$28.42**
Capital Cost	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**	**$0**

*Note: Machines and facility used for the ATR will also be used to create the desulfurizer; therefore no additional capital cost is incurred for desulfurizer manufacturing.

5.2.3 *Heat Exchanger*

To provide a basis for DFMA™ analysis we assumed the heat exchangers would be fabricated from corrugated thin gage 310 SS stock and high-temperature furnace brazed or laser welded to yield sealed assemblies. In early production, the heat exchangers are likely to be identical and sized for the highest heat duty. This choice enables single SKU component stocking and allows tooling and set-up costs to be spread over a greater number of parts. As system designs mature and product sales volumes develop, specialization and design-to-purpose will bring down costs as well as decrease overall system size. In the absence of a more detailed design, we did not include benefits of specialization except through the sensitivity analysis.

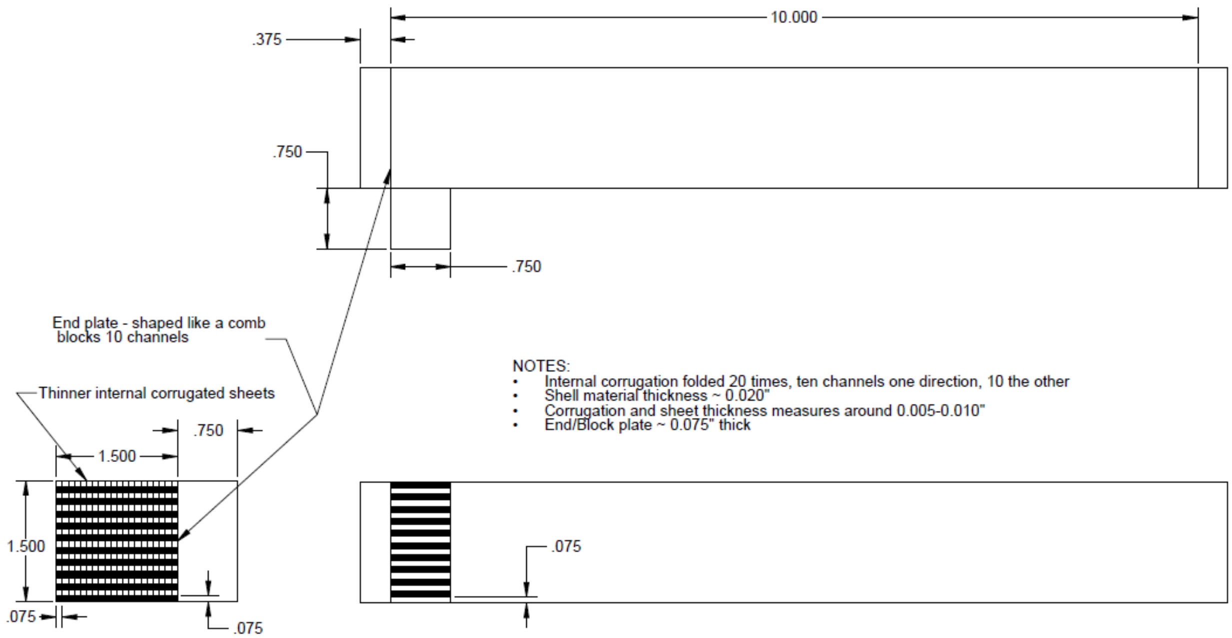


Figure 5-3. Heat Exchanger Dimensions

Table 5-17. Heat Exchanger Cost Summary

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Material	$210.39	$210.39	$210.39	$210.39	$210.39	$210.39	$210.39	$210.39
Labor	$9.00	$3.73	$1.13	$0.39	$9.00	$3.73	$1.13	$0.39
Machine	$6.70	$6.70	$6.70	$6.70	$6.70	$6.70	$6.70	$6.70
Scrap	$2.39	$2.39	$2.39	$2.39	$2.39	$2.39	$2.39	$2.39
Tooling	$3.71	$3.71	$3.71	$3.71	$3.71	$3.71	$3.71	$3.71
Part Cost	$228.48	$223.21	$220.61	$220.27	$228.48	$223.21	$220.61	$220.27
Assembly	$22.34	$21.61	$21.26	$21.15	$22.34	$21.61	$21.26	$21.15
Total Cost	$250.82	$244.82	$241.87	$241.42	$250.82	$244.82	$241.87	$241.42

5.3 Electrical System Cost Assumptions

The cost for the electrical system is primarily driven by the DC/DC converter. The system controller and sensors comprise the next largest portion of the cost. Protective devices and interconnecting components complete the remainder of the electrical system cost.

5.3.1 DC/DC Converter

The DC/DC converter cost for the 1 kW and 5 kW system are estimated based on an averaged cost at each quantity of the converter estimates obtained from power electronics vendors for that system. Additionally, the 5 kW converter costs use the 1 kW numbers and apply a scale factor of five for comparison. This approach was used because the converters can be connected in parallel to obtain higher output power. The higher number of converters used to produce a single system drives down the cost per system and the converters used in the estimation were capable of more than the necessary power.

The cost of power conversion products is based largely on production volumes. The primary components in a buck converter are circuit card assemblies (CCAs), an inductor, power transistors, bulk storage capacitors, control and communication circuitry, packaging and heat transfer components (finned heat sinks or liquid cooling plates). Because the voltage used in auxiliary power applications is relatively low, the current levels are quite large (e.g. 5 kW @ 12 volts – 416 amps). High current converter designs implement one of two approaches, several smaller converters working together in parallel or one large converter. The tradeoffs for this decision are usually dictated by the required voltages and power, availability of components in the voltage and current ranges required, and cost. At high current levels, the copper plating thickness of the traces on the printed wiring board (PWB) typically drives up the cost of the PWB that houses the power circuitry. The cost of the inductors, power transistors, and integrated circuits (ICs) used for the design are based solely on quantity and component selection. Manufacturing costs are based on quantity at the unit level. At present there is not a high demand for DC-DC converters that are used in fuel cell APU applications. Some ways to potentially reduce the cost of DC-DC converters would be to leverage similar products used by other industries that are produced in mass and to refine manufacturing processes that reduce cost. Another factor that increases the cost of the converter in this application is the need to interface with the fuel cell and the batteries.

Based on the research conducted, there are few or no manufacturers that produce DC-DC converters of this type in mass quantities. If the demand for these converters were present, competition would increase and the economy of scale would likely drive cost down some at high quantities; however, 10,000 units may not be a large enough number to justify large cost savings. But, the fact remains that the individual components used in DC-DC converter designs requiring high current are not cheap and to some extent are dependent on the market value of the raw materials. For example, copper is used in large amounts because of the high current inherent to material handling applications (low voltage, high power) so the cost of PWB plating, connectors, wire and cable, power transistors, etc. will fluctuate with the cost of the raw material.

5.3.2 Controller and Sensors

The system controller cost was estimated based on previous efforts completed at Battelle and OEM automotive Electronic Control Unit (ECU) cost. We assumed that the system controller is a custom circuit card assembly built around a micro-controller that handles the specific needs of the system. Because of the similarity to an automotive system ECU, the system controller would probably have some of the same features as an automotive ECU and as such the cost of OEM ECUs was used to estimate the higher quantity cost of the controller. The current sensor and voltage sense circuitry are readily available components and as a result the cost for those components could be identified via the internet. The cost for a hydrogen sulfide sensor was found on the internet[35], but gas sensors designed specifically for this application (simple and affordable threshold detectors) were not found. As a result, the cost for the hydrogen sulfide sensor reflects a single venders price for a sensor that has more features and capability than are required.

5.3.3 Protection and Interconnects

The contactors and fuses used in fuel cell applications typically require high current and low DC voltage ratings. The manufacturers that supply these types of devices are somewhat limited. The cost of these components is an average of the component costs obtained from the internet and quoted prices from authorized distributors of the products. The power connector used to connect the system was assumed to be an Anderson style connector and the costs reflect the average cost of that component in the appropriate amperage rating. It was assumed that busbar is required because of the volume constraints in the system. The busbar is used to connect the fuel cell output to the DC/DC converter and the battery. The price for the busbar used a length of 2 ft x ¼"x1" copper bar. The cost for the connectors and other interconnection cable was estimated based on figures from the Battelle 2011 report.[36]

5.4 Balance of Plant Cost Assumptions

The costs associated with the BOP components are tabulated in Table 5-18 and Table 5-19. Figure 5-4 and Figure 5-5 compare component costs at a subcategory level similar to the system schematic. At a production rate of 1,000 systems a year, the BOP hardware is estimated to cost nearly $8,200 for one 1 kW system and $9,800 for 5 kW.

A category titled "Additional Work Estimate" is included to capture any small contingencies not specifically itemized in this report. This includes components such as heat sinks and fans for additional electrical cooling, supplementary temperature or pressure sensors, and any extra assembly hardware. This estimate was developed around a 20% buffer to the electrical subsystem cost, and a 10% buffer to all remaining hardware.

For components not detailed above, the items are assumed commercially avaialable and therefore quotes or budgetary pricing were used.

[35] http://www.alphasense.com/index.php/products/hydrogen-sulfide/

[36] Battelle. 2011. The High Volume Manufacture Cost Analysis of 5 KW Direct Hydrogen Polymer Electrolyte (PEM) Membrane Fuel Cell for Backup Power Applications. Report to the DOE. DOE Contract No. DE-FC36-03GO13110.

Table 5-18. Component Costs for the 1 kW APU System

Component Description	Annual Production of 1 kW APU Systems				
	1	100	1,000	10,000	50,000
Fuel Ball Valve	$34	$31	$27	$27	$27
Fuel Pump	$408	$367	$326	$326	$326
Fuel Flow Meter	$0	$0	$0	$0	$0
Fuel Injector	$126	$113	$101	$101	$101
Pressure Regulator	$110	$99	$88	$88	$88
Water Pump	$408	$367	$326	$326	$326
Water Flow Meter	$0	$0	$0	$0	$0
Water Tank	$53	$48	$42	$42	$42
Exhaust Condenser	$300	$300	$270	$240	$240
Filter & Housing	$313	$215	$166	$134	$134
Blower (Cathode Air)	$381	$346	$305	$305	$305
Blower (Anode Air)	$381	$346	$305	$305	$305
Flowmeter (Cathode Air)	$160	$144	$128	$128	$128
Flowmeter (Anode Air)	$160	$144	$128	$128	$128
Startup Bypass Valve	$34	$31	$27	$27	$27
Reformer Air Preheater	$411	$411	$370	$329	$329
Steam Generator	$411	$411	$370	$329	$329
Superheater	$411	$411	$370	$329	$329
Reformate Heater	$411	$411	$370	$329	$329
Cathode Air Heater	$411	$411	$370	$329	$329
Afterburner	$512	$467	$417	$416	$416
DC/DC Converter (Power)	$250	$210	$194	$155	$155
Fuel Cell ECU	$800	$500	$300	$175	$175
System Controller	$800	$500	$300	$175	$175
Bus Bar	$32	$17	$16	$14	$14
Fuses	$38	$37	$37	$36	$36
DC/DC Converter (Controls)	$84	$76	$72	$68	$68
Connector Power	$30	$24	$21	$18	$18
Contactors	$100	$72	$64	$60	$60
Wiring & Connectors	$249	$237	$216	$194	$194
Stack Anode Pressure Sensor	$395	$375	$375	$375	$375
Temperature Sensors	$125	$95	$55	$40	$40
Current Sensor	$32	$14	$11	$9	$9
Voltage Sensor	$55	$50	$43	$39	$39
H_2S Sensor	$243	$243	$219	$210	$210
Assorted Plumbing/Fittings	$495	$448	$407	$365	$365
Assembly Hardware	$30	$28	$26	$23	$23
Frame & Housing	$219	$209	$190	$171	$171
Reformer	$389	$370	$336	$303	$303
Desulfurizer	$19	$18	$17	$15	$15
Additional Work Estimate	$1,100	$1,000	$800	$700	$700
Total Cost	**$10,920**	**$9,597**	**$8,204**	**$7,383**	**$7,383**

Table 5-19. Component Costs for the 5 kW APU System

Component Description	Annual Production of 5 kW APU Systems				
	1	100	1,000	10,000	50,000
Fuel Ball Valve	$34	$31	$27	$27	$27
Fuel Pump	$408	$367	$326	$326	$326
Fuel Flow Meter	$0	$0	$0	$0	$0
Fuel Injector	$126	$113	$101	$101	$101
Pressure Regulator	$110	$99	$88	$88	$88
Water Pump	$408	$367	$326	$326	$326
Water Flow Meter	$0	$0	$0	$0	$0
Water Tank	$53	$48	$42	$42	$42
Exhaust Condenser	$410	$410	$369	$328	$328
Filter & Housing	$313	$215	$166	$134	$134
Blower (Cathode Air)	$508	$462	$406	$406	$406
Blower (Anode Air)	$381	$346	$305	$305	$305
Flowmeter (Cathode Air)	$160	$144	$128	$128	$128
Flowmeter (Anode Air)	$160	$144	$128	$128	$128
Startup Bypass Valve	$34	$31	$27	$27	$27
Reformer Air Preheater	$411	$411	$370	$329	$329
Steam Generator	$411	$411	$370	$329	$329
Superheater	$411	$411	$370	$329	$329
Reformate Heater	$411	$411	$370	$329	$329
Cathode Air Heater	$411	$411	$370	$329	$329
Afterburner	$512	$467	$417	$416	$416
DC/DC Converter (Power)	$1,709	$1,438	$1,325	$1,062	$1,062
Fuel Cell ECU	$800	$500	$300	$175	$175
System Controller	$800	$500	$300	$175	$175
Bus Bar	$32	$17	$16	$14	$14
Fuses	$38	$37	$37	$36	$36
DC/DC Converter (Controls)	$84	$76	$72	$68	$68
Connector Power	$30	$24	$21	$18	$18
Contactors	$100	$72	$64	$60	$60
Wiring & Connectors	$249	$237	$216	$194	$194
Stack Anode Pressure Sensor	$395	$375	$375	$375	$375
Temperature Sensors	$125	$95	$55	$40	$40
Current Sensor	$32	$14	$11	$9	$9
Voltage Sensor	$55	$50	$43	$39	$39
H_2S Sensor	$243	$243	$219	$210	$210
Assorted Plumbing/Fittings	$495	$448	$407	$365	$365
Assembly Hardware	$30	$28	$26	$23	$23
Frame & Housing	$219	$209	$190	$171	$171
Reformer	$452	$430	$391	$352	$352
Desulfurizer	$32	$31	$28	$25	$25
Additional Work Estimate	$1,500	$1,200	$1,000	$900	$900
Total Cost	**$13,092**	**$11,323**	**$9,802**	**$8,738**	**$8,738**

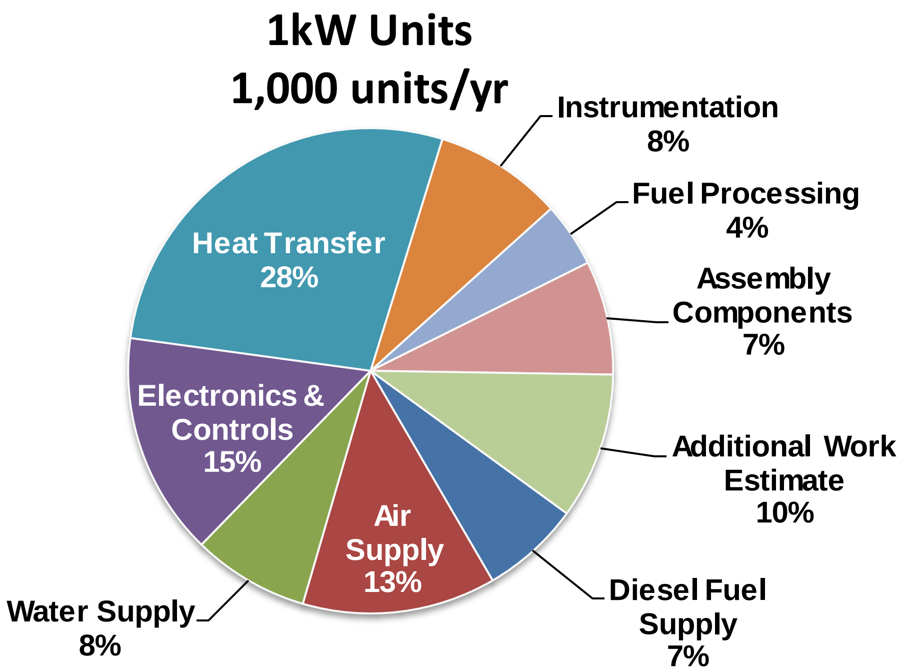


Figure 5-4. Distribution of Costs across BOP Components for 1 kW Design.

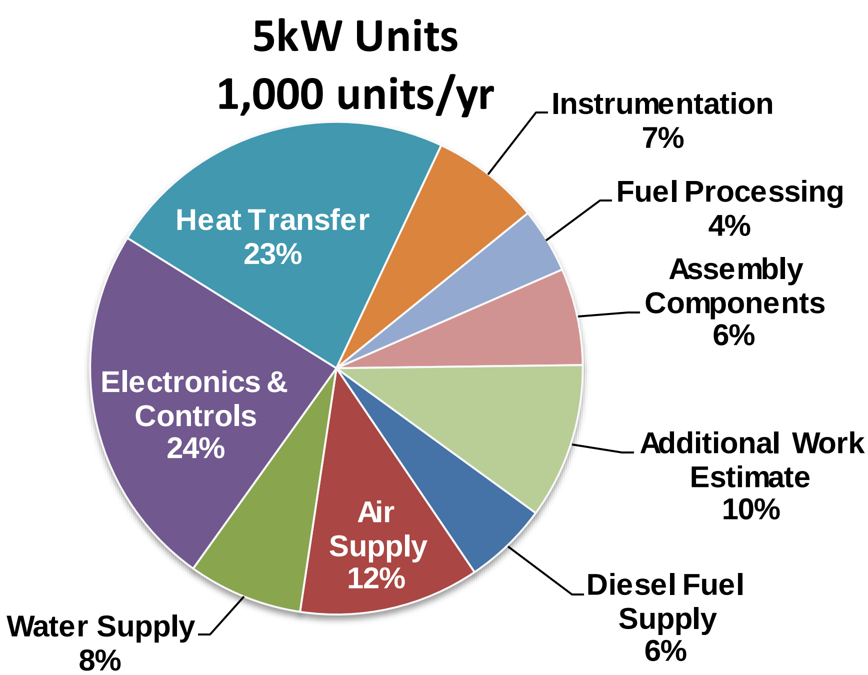


Figure 5-5. Distribution of Costs across BOP Components for 5 kW Design.

5.4.1 Future Cost Reductions

The items below are potential areas for product or manufacturing improvement. Additional work and discussion is contained in Section 8 – Sensitivity Analysis.

Heat Exchangers are by far the largest area for balance of plant cost reduction , accounting for 22–28% of the total BOP hardware cost depending on the annual production rate and system size. In general system integrators are developing many of their own BOP components, including heat transfer components. While there are some heat exchanger manufacturers with OEM or custom sized hardware options, they do not have experience with the small scale high temperature equipment required for the APU market. These two factors mean there are almost no COTS options and little cost information. For this reason, Battelle chose a relatively simple design based on publicly available information to develop DFMA™ cost model. This also means there is significant room for cost reduction and design optimization.

The **DC/DC converter** is a substantial expense as well, specifically in the larger 5kW system. Depending on the annual production rate, the main power DC/DC converter accounted for 12-14% of the overall BOP hardware cost. Alternative electrical system designs exist that seek to simplify or reduce the component cost in the system by removing the DC/DC converter and directly connecting the fuel cell to the batteries. This approach eliminates the cost of the converter at the potential expense of more complicated battery management electronics, additional electronics to manage power flow, a more stringent integration with vehicle batteries, and possibly a more involved stack design.

A current trend in SOFC APU development is the use of **Anode Gas Recirculation (AGR)**. While Battelle did not incorporate this mehod of heat and water recovery, for reasons mentioned above, there is potential for this approach to simplify BOP design and reduce overall costs. Like the heat exchangers, development of the blower required for this operation is widely performed in house by system integrators; therefore, there is little or no information regarding design or cost. According to literature and stakeholder feedback, the most significant value added by the use of AGR is increased system efficiency and reduced number of heat exchangers. However, preliminary analysis of AGR blower operation requirements suggest the high temperature materials and configuration may not significantly reduce systems costs when used in place of extra heat exchangers. Additionally, stack exhaust may still need to be cooled to some degree before entering the recirculation blower. The incorporation of AGR into the system design may be an area of interest for future work.

Finally, two areas for cost reduction that have been mentioned by system integrators and industry stakeholders are: **removal of the desulfurization components**, and **integration of waste heat recovery** to provide cabin heat (rather than using the APU for strictly electrical power). Mixed feedback from integrators and projections based on current SOFC development trends indicate many of the limitations due to fuel sensitivity are being solved at the cell level. Specifically, several stack manufacturers are increasing the level of sulfur tolerance in their SOFC technology. The availability of sulfur tolerant stacks coupled with continuously reduced levels of sulfur compounds in commercial diesel fuel may allow for the removal of fuel desulfurization components. However, existing SOFC stack technology still suffers immediate power loss and increased degradation rates in the presence of sulfur compounds.

Although this study is focused on stand alone fuel cell APU systems, long haul truck APU's are generally used to power cabin climate control and hotel loads. The high temperature nature of the SOFC unit provides a significant amount of waste heat. Utilization of the waste heat for cabin heating or thermal refrigeration unit would greatly reduce the total cost of complete truck accessories; specifically, inclusion of heating and cooling components means stand alone units would not be required.

5.5 System Assembly and Learning Curve Assumptions

The DFMA™ software produces an assembly cost based on hand assembly at its most efficient, which is $94.65 for the rest of the APU system. The learning curve analysis essentially backs that number up to a time when bugs are still being worked out of the assembly process. This additional time adds a slight cost to the base assembly cost. Total system assembly costs are summarized in Table 5-20, which includes a learning curve. Complete calculations are available in Appendix A.12.

Table 5-20. Summary System Assembly Cost Assumptions

1st Year Average Assembly Cost per Stack				
	Stacks per year			
	100	1,000	10,000	50,000
System	$121.92	$ 97.38	$ 94.92	$ 94.70

5.6 Capital Cost Assumptions

The following tables provide details on the cost assumptions for the components that make up the total capital cost.

Table 5-21. Summary of Captial Cost Assumptions

Capital Cost	Unit Cost	Units	Assumption/Reference
Factory Total Construction Cost	250	$/sq.ft.	• Includes Electrical Costs ($50/sq.ft.). Total plant area based on line footprint plus 1.5x line space for working space, offices, shipping, etc. • Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks.
Production Line Equipment Cost	Varies by component		• Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks.
Forklifts	25,000	$/lift	• With extra battery and charger.
Cranes	66,000	$/crane	• Assumes 5 ton capacity, 20' wide per line
Real Estate	125,000	$/acre	• Assumes vacant land, zoned industrial Columbus, OH
Contingency	10% CC		• Typical construction estimate assumption

Table 5-22. Summary of Captial Costs ($000)

	1 kW				5 kW			
	100	1,000	10,000	50,000	100	1,000	10,000	50,000
Factory Total Construction Cost	$1,134	$1,167	$1,538	$4,431	$1,134	$1,167	$1,777	$6,736
Production Line Equipment Cost	$3,075	$3,225	$4,725	$15,291	$3,075	$3,225	$5,782	$26,334
Forklifts	$50	$50	$50	$100	$50	$50	$50	$200
Cranes	$198	$198	$198	$396	$198	$198	$198	$792
Real Estate	$125	$125	$125	$250	$125	$125	$125	$1,000
Contingency	$459	$477	$664	$2,047	$459	$477	$794	$3,507
Total	$5,041	$5,242	$7,300	$22,515	$5,041	$5,242	$8,726	$38,569

6 Limitations of the Analysis

The approach for the analysis is to create a generic system that is representative of current industry technology and practice. The generic system is made from the merged non-proprietary input from multiple industry representatives and is defined at a high level. There are numerous tradeoffs to be considered when choosing a specific design feature or system specification characteristic. Since the decisions made to define the design and specification are the basis for the cost analysis, it is worthwhile to explicitly consider the impact, limitations, and justification for the choices made.

6.1 Manufacturing Costs

Stack costs are based on the use of typical manufacturing processes for the construction of the individual cells. These include creation of the supporting anode, cell blanking, ceramic layer deposition, kiln firing, and sintering.

Alternative and innovative manufacturing techniques were not evaluated. Based on industry feedback, the techniques used for the cost analysis are consistent with existing processes used by SOFC stack component manufacturers.

Table 6-1. Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives not Evaluated
Ceramic deposition	Screen printing	Plasma spray coating
	Tape casting	
Interconnect	Sheet metal stamping, etching	Laser cutting, water jet cutting, chemical etching
	Spray deposition coating	
Sealing	Bead deposition	Screen printing, tape casting
Picture frame	Sheet metal stamping	Laser cutting, water jet cutting.
End plate	Die casting	Stamping, welding
	Machining (not chosen)	

6.2 Balance of Plant Hardware Costs

Balance of plant hardware costs are subject to two primary limitations; limited cost savings at high volume and lack of previous work covering fuel cells for APU applications.

An annual production volume increase from 1,000 and 10,000 units did not generate a significant level of volume discount pricing for the highly specialized purchased parts. Similarly, Battelle does not expect much price reduction with an increased volume to 50,000 units per year. There seem to be two significant hurdles to further cost reduction at higher volumes: flat or fixed material costs, and limited component volumes. Bulk commodity materials used in much of the hardware have relatively fixed costs unless purchased at very low quantities. Conversely, certain specialty components (e.g. fuel reformer, compact heat exchangers, etc) required to meet the rigorous specification of the APU system are not readily available at high volumes, therefore it was either difficult or impossible to obtain quotes for volumes at or above those required for 10,000 units.

Many of the studies that focus on the integration of fuel cells in new or existing markets tend to focus mainly, or completely, on the technology and costs associated strictly with cell and stack production. Further, they have failed to account for the cost of the BOP components, which turn out to be a major cost driver for the system. Unfortunately, SOFC system integration has not yet reach a level of maturity to warrant a uniform system design or multiple BOP supplier options. Therefore, BOP commercial hardware options are relatively limited and expensive.

7 Cost Analysis Results

This section presents the results of the four manufacturing volumes for 1 and 5 KW APU SOFC fuel cell systems, including fuel cell stack, BOP, as well as overall system costs.

7.1 1 kW Cost Analysis Results

The stack manufacturing costs for the 1 kW SOFC stack are broken down by component in Table 7-1. The major contributors to the stack costs are the cells and interconnects contributing to 31% and 34% of the total stack cost respectively (based on 10,000 units). Figure 7-1 shows the distribution of costs of the stack.

The BOP costs for the 1 kW SOFC system are broken down by component in Table 7-2. The major contributors to the BOP costs are the heat exchangers, air supply and electronics contributing to 28%, 14% and 12% of the total stack BOP respectively (based on 10,000 units). Figure 7-2 shows the distribution of costs for the BOP for the 1 kW system.

The total system cost breakdown is shown in Table 7-3 showing that the BOP cost is the primary driver.

Table 7-1. 1 kW APU SOFC Stack Manufacturing Cost Summary

Stack Component	100 Units	1000 Units	10,000 Units	50,000 Units
Cells	$246	$177	$149	$142
Interconnects	$170	$167	$167	$167
Picture Frame	$5	$5	$5	$5
Sealing	$28	$26	$25	$25
End Plates	$50	$44	$44	$44
Assembly Hardware	$74	$74	$74	$74
Stack Assembly	$15	$12	$12	$12
Stack Brazing	$3	$6	$6	$6
Total	**$590**	**$511**	**$481**	**$473**

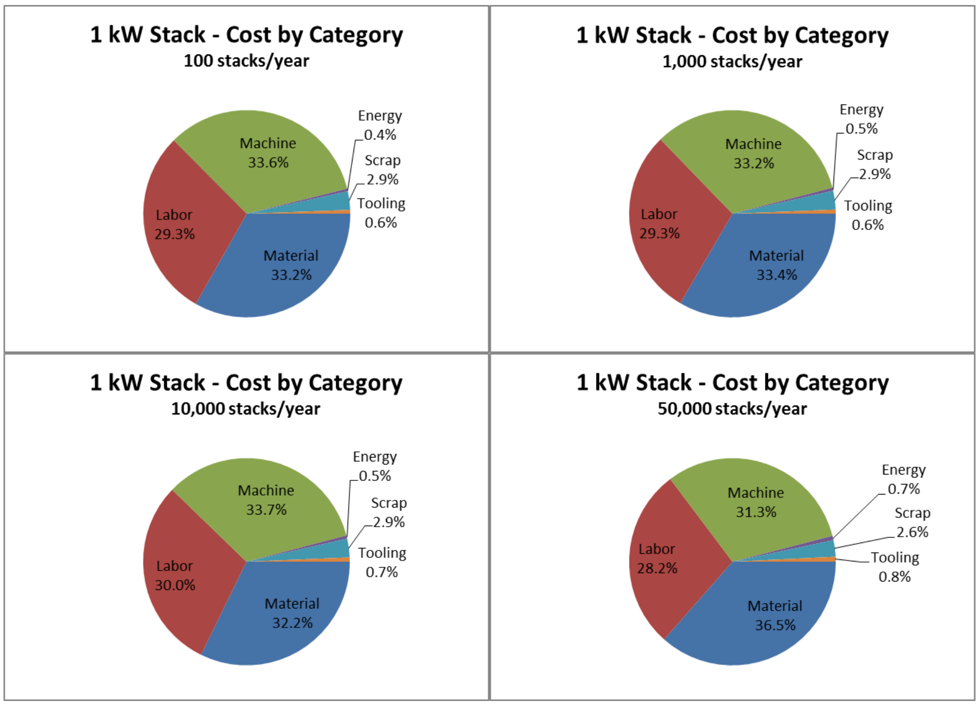


Figure 7-1. Cost Breakdown of 1 kW Stack

Table 7-2. 1 kW APU SOFC BOP Cost Summary

BOP Component	100 Units	1,000 Units	10,000 Units	50,000 Units
Fuel Supply	$610	$542	$542	$542
Air Supply	$1,226	$1,059	$1,027	$1,027
Water Supply	$715	$638	$608	$608
Power Electronics and Controls	$1,673	$1,220	$895	$895
Heat Transfer Components	$2,522	$2,267	$2,061	$2,061
Instruments and Sensors	$777	$703	$673	$673
Fuel Reformer/Desulfurizer	$388	$353	$318	$318
Additional Components	$685	$623	$559	$559
Additional Work Estimate	$1,000	$800	$700	$700
Total	**$9,597**	**$8,204**	**$7,383**	**$7,383**

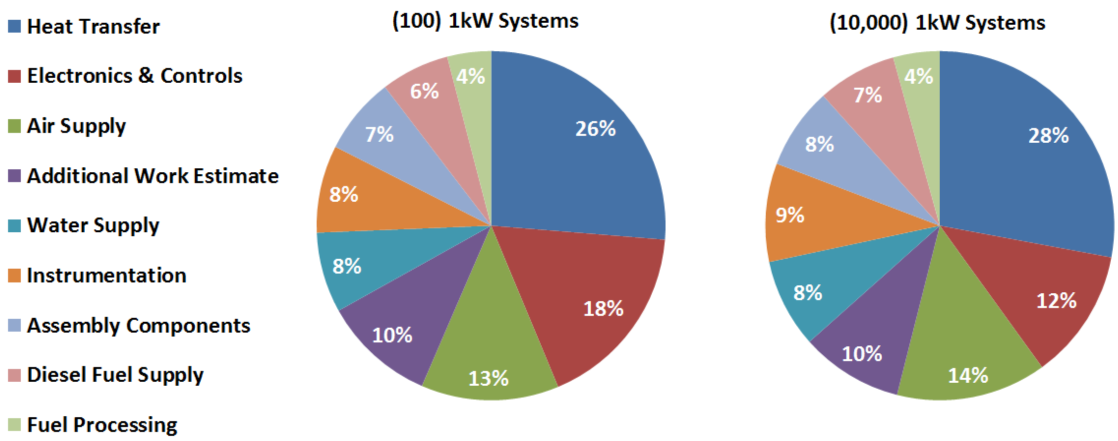


Figure 7-2. 1 kW APU SOFC BOP Hardware Cost Breakdown

Table 7-3. 1 kW APU SOFC System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$590	$511	$481	$473
Annualized stack manufacturing capital cost	$4,757	$495	$69	$43
BOP	$9,597	$8,204	$7,383	$7,383
System assembly, test, and conditioning	$475	$451	$448	$448
Total system cost, pre-markup	$15,419	$9,661	$8,381	$8,347
System cost per net KW, pre-markup	$15,419	$9,661	$8,381	$8,347
Sales markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	$23,129	$14,491	$12,571	$12,520
System cost per net KW, with markup	$23,129	$14,491	$12,571	$12,520

7.2 5 kW Cost Analysis Results

The stack manufacturing costs for the 5 kW SOFC fuel cell stack are broken down by component in Table 7-4. The major contributors to the stack costs are the cells and the interconnects, contributing to 35% and 44% of the total stack cost respectively (based on 10,000 units). Figure 7-3 shows the distribution of costs of the stack.

The BOP costs for the 5 kW SOFC system are broken down by component in Table 7-5. The major contributors to the BOP costs are the heat exchangers, electronics (including DC/DC Converter), and air supply contributing to 24%, 21% and 13% of the total system cost respectively (based on 10,000 units). Figure 7-4 shows the distribution of BOP costs.

The total system cost breakdown is shown in Table 7-6 showing that the BOP cost is the primary driver.

Table 7-4. 5 kW APU SOFC Stack Manufacturing Cost Summary

Stack Component	100 Units	1,000 Units	10,000 Units	50,000 Units
Cells	$618	$483	$425	$416
Interconnects	$586	$583	$583	$583
Picture Frame	$14	$14	$14	$14
Sealing	$73	$72	$70	$64
End Plates	$72	$65	$64	$64
Assembly Hardware	$74	$74	$74	$74
Stack Assembly	$27	$21	$21	$21
Stack Brazing	$12	$16	$16	$16
Total	**$1,476**	**$1,327**	**$1,267**	**$1,257**

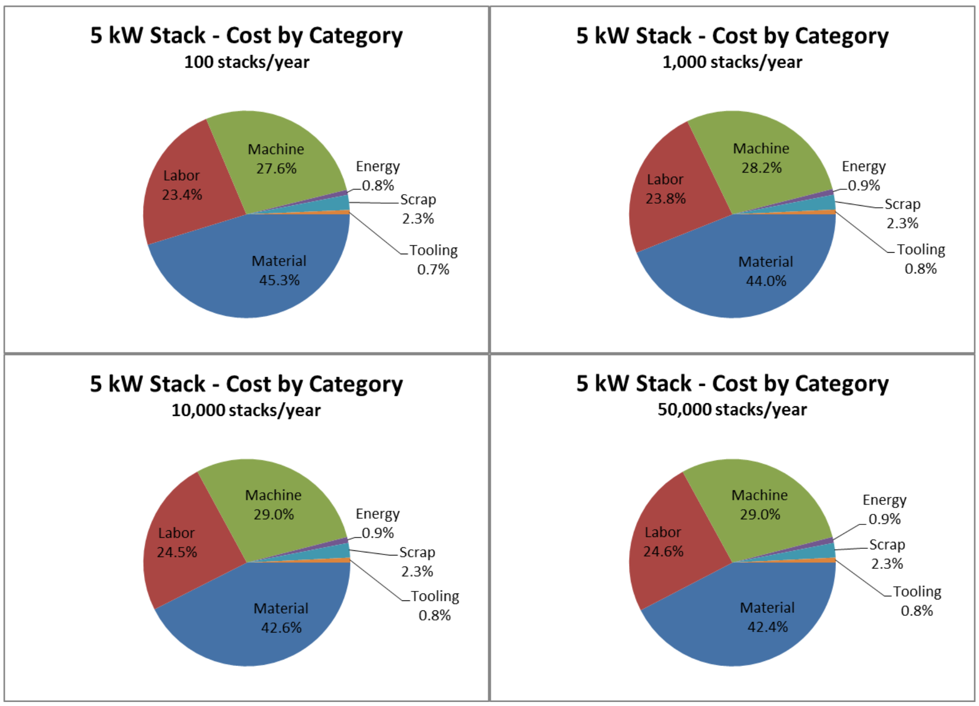


Figure 7-3. Cost Breakdown of 5 kW Stack

Table 7-5. 5 kW APU SOFC BOP Cost Summary

BOP Component	100 Units	1,000 Units	10,000 Units	50,000 Units
Fuel Supply	$610	$542	$542	$542
Air Supply	$1,342	$1,160	$1,128	$1,128
Water Supply	$825	$737	$696	$696
Power Electronics and Controls	$2,901	$2,351	$1,802	$1,802
Heat Transfer Components	$2,522	$2,267	$2,061	$2,061
Instruments and Sensors	$777	$703	$673	$673
Fuel Reformer/Desulfurizer	$461	$419	$377	$377
Additional Components	$685	$623	$559	$559
Additional Work Estimate	$1,200	$1,000	$900	$900
Total	**$11,323**	**$9,802**	**$8,738**	**$8,738**

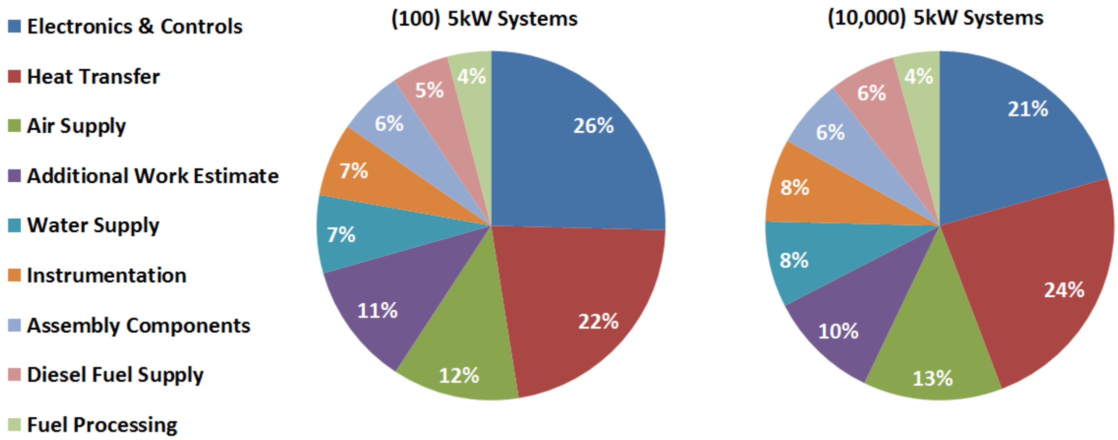


Figure 7-4. 5 kW APU SOFC BOP Hardware Cost Breakdown

Table 7-6. 5 kW APU SOFC System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$1,476	$1,327	$1,267	$1,257
Annualized stack manufacturing capital cost	$4,757	$495	$82	$73
BOP	$11,323	$9,802	$8,738	$8,738
System assembly, test, and conditioning	$481	$456	$454	$454
Total system cost, pre-markup	$18,037	$12,080	$10,541	$10,522
System cost per net KW, pre-markup	$3,608	$2,416	$2,108	$2,104
Sales markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	$27,056	$18,120	$15,812	$15,783
System cost per net KW, with markup	$5,411	$3,624	$3,162	$3,157

8 Sensitivity Analysis

The sensitivity analysis of the costs for 1kW and 5kW BOP components at the 10,000 unit production volume explores the impact of specific variations to the assumptions for major contributing cost factors and highlights their significance. The cost factors were chosen because of their significant contribution to the system costs and/or the difficult nature of precisely assessing their magnitude, such as not Commercial-Off-The-Shelf (COTS) items like high temperature heat exchangers. The analysis demonstrates the effect to the overall cost of the BOP system based on reasonable variations to each factor.

The cost factors that were varied for the analysis include:

- Fuel Injector cost
    - Assumed to be moderate pressure/high temperature hybrid of diesel and gasoline OEM, $101/ea
    - Adjusted to cost of diesel OEM ($303/ea) and cost of gasoline DI OEM ($75/ea)
    - Varied by +300%/-26%
- Adjusted Heat Exchanger cost
    - Assumed to be non-optimized single size item at $329/ea

- Adjusted to optimized $309/ea for 5kW system and $97/ea for 1kW system
    - Production costs generated with DFMA™ program using public design and patent info for input variables.
- Air Flow meter
    - Assumed to be MAF type automotive sensor at $128/ea
    - Adjusted cost to OEM numbers used in MHE study and 2009 DTI study.
    - Varied by +0%/-27%
- No DC-DC Converter
    - Assumed market price for COTS items
    - Adjusted cost to $0 assuming control system could tolerate load demand
    - Assumption based on industry feedback from specific integrators who have eliminated the converter from their systems
- No desulfurizer, and 1 less heat exchanger
    - Assumed cost based on research and DFMA™ results
    - Adjusted costs for removal of desulfurizer and associated heat exchangers
    - Assumption based on industry feedback from integrators who have removed the desulfurizer from their system, assumes sulfur tolerant SOFC technology
- Liquid pump cost
    - Assumed precision metering pumps for fuel and water management (lab grade equipment)
    - Adjusted cost to OEM components for both pumps, utilizing injectors and ECU for metering
    - Varied costs by +0%/-50%

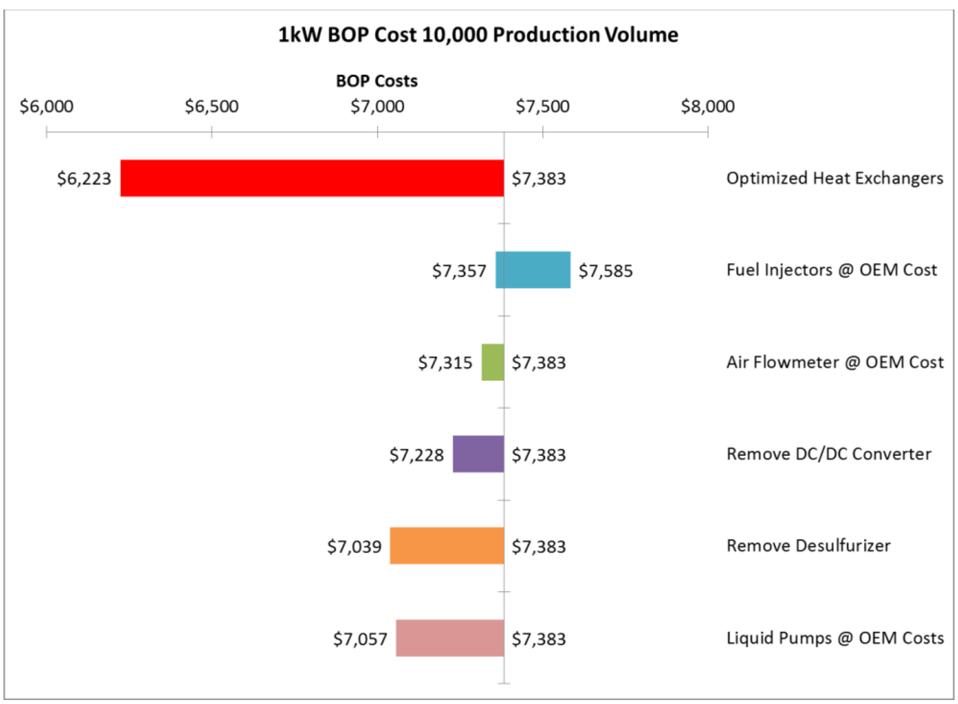


Figure 8-1. Sensitivity Analysis: 1 kW BOP Cost – 10,000 Production Volume

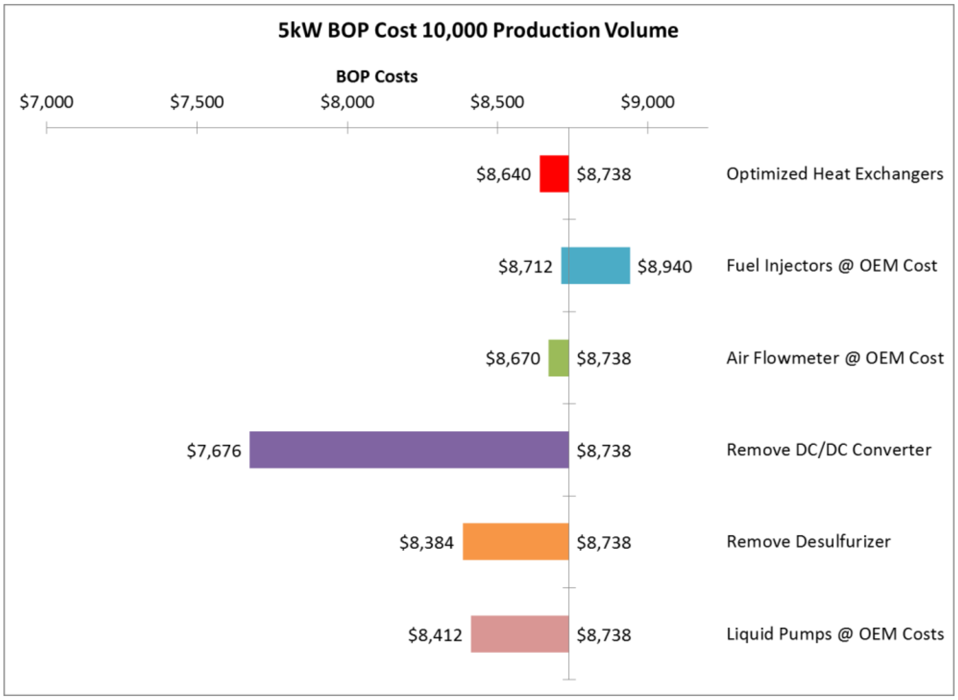


Figure 8-2. Sensitivity Analysis: 5 kW Stack Cost – 10,000 Production Volume

The heat exchangers and DC/DC Converter are the two biggest factors affecting the cost of the 1kW and 5kW systems, respectively. The cost per heat exchanger used in the model ($329/ea) is based on a single sized item and costs determined through use of DFMA™ analysis. The current trend with system integrators indicates much of their heat transfer components are internally developed and produced. While the use and cost for a DC/DC converter in the 5kW system ($1062) is fairly standard for this size item, it has been suggested by system integrators to design the system control electronics such that a converter is not required. As shown, significant costs are saved to the BOP total.

Our system integrator survey found that many system integrators are utilizing internally developed proprietary components for the heat transfer hardware, therefore obtaining accurate quotes for these items was not possible. Certain limitations with the COTS option, including exceptionally high cost, limited sizing, and no commercially available alternatives, led our team to perform the DFMA™ on this item. Using the public information for the design of the commercial option, Battelle assumed all of the necessary process steps and materials to achieve the annual volume required. However, since this item was not designed or sized specifically for our application, the sensitivity analysis indicates that further refinements of this nature would drastically reduce the cost contribution to the system. In other words, our baseline cost assumption for the heat exchanger is slightly conservative for the 5kW system, but extremely conservative for the 1kW BOP. Proper sizing and optimization of the heat transfer components is critical to reducing cost of smaller APU systems.

As mentioned above, alternative electrical system designs exist that seek to simplify or reduce the component cost in the system by removing the DC/DC converter and directly connecting the fuel cell to the batteries. This approach eliminates the cost of the power converter at the expense of incorporating more complicated battery management electronics, additional electronics to manage power flow, a more stringent integration with vehicle batteries, and possibly a more involved stack design. It is assumed these costs would be wrapped up in non-recurring engineering (NRE) and not impact the cost of control electronics.While this may not lead to significant cost savings on smaller units, Figure 8-2 shows that removal of the power converter from the 5kW unit would result in a 12% cost reduction and cost per gross kW of $1,559 before mark-up.

9 Lifecycle Cost Analysis of Fuel Cells

Fuel cell systems will compete with battery powered systems, internal combustion engine systems, and simply engine idling for application on long haul trucks. Fuel cell APU's offer a number of advantages over conventional technologies including fuel cost savings, reduced maintenance, and environmental benefits. However, fuel cell systems continue to have a higher first cost than conventional alternatives.

This analysis looks to compare the lifecycle costs of fuel cell powered systems to truck engine idling and internal combustion systems for Class 8 Long Haul Trucks to identify the biggest cost drivers. The analysis is based on Battelle's analysis of the manufacturing costs of the fuel cell system without markup. The characteristics of operation are based on time that would normally be classified as discretionary truck idling time, between 1,800 and 2,400 hours per year (assumed to be 2,000 hours for this analysis). In this scenario, power requirements mainly serve to maintain driver comfort levels[37,38] with a base load of 2kW. Based on a fuel cell life of 10,000 hours, the fuel cell is replaced every three years; this takes into account the additional run time required for start-up and shutdown of the SOFC system. The $3.50 per gallon cost of diesel used in this analysis assumes that storage and delivery costs are amortized in the fuel cost[39]. A discount rate of 8% and an inflation rate of 1.9% are applied. No disposal costs are assumed for any of the technologies. It is assumed that disposal costs are included in the initial capital cost of the system or that manufacturers allow trade-in of old systems. Assumptions are shown in Table 9-1.

Table 9-1. Cost Assumptions for Fuel Cell APU, Internal Combustion Engine APU and Idling Truck Engine

	Fuel Cell	ICE Genset	Idling Truck Engine
Retail Cost of Power System	$10,541	$7,500	-
Power Source	5 kW SOFC Stack	15hp Diesel Engine	400hp Diesel Engine
Hours of Operation per Year (Hrs)	2,000	2,000	2,000
Energy Efficiency	30%	25%	3-4%
Fuel Consumption per Hour (gal/hr)	0.22	0.30	0.72[40]
Maintenance Cost (per hour)	$0.05	$0.07	$0.15
Fuel Cost (per hour)	$0.77	$1.05	$3.50
Heater and Air Conditioner	$1,800	-	$1,800
Installation Cost	$1,500	$1,500	-
O & M Cost over 3 Years	$300	$420	$900
Fuel Cost over 3 Years	$4,620	$6,300	$15,120
Total Cost over 3 Years	$**18,761**	$**15,720**	$**17,820**

[37] Brodrick C, Brodrick Lipman TE, Farshchi M, Lutsey NP, Dwyer HA, Sperling D. et al. Evaluation of fuel cell auxiliary power units for heavy duty diesel trucks. Transportaion Research Part D 2002;7:303–15.

[38] P Agnolucci, Prospects of fuel cell auxiliary power units in the civil markets. International Journal of Hydrogen Energy 32 (2007) 4306-4318

[39] Price determined using national average on-highway diesel fuel price for July, 2013 with listed adjustments, from US Energy Information Administration, http://www.eia.gov/petroleum/gasdiesel/

[40] L Gaines, CJ Drodrick Hartman, Energy Use and Emissions Comparison of Idling Reduction Options for Heavy-Duty Diesel Trucks. Paper 09-3395 for January meeting of Transportation Research Board, 2009

The results of this analysis indicate the Internal Combustion Engine APU is the most cost effective alternative at this stage of development; this is the case for a few reasons: 1) capital cost of fuel cell is still higher due to early market entry phase and high cost BOP components, 2) analysis does not take into account incentives or tax credits, 3) it is assumed none of the waste heat from the SOFC system is being recuperated for cabin climate control.

Under the current assumptions for 2,000 hour per year operation, the Net Present Value (NPV) of the total capital costs, operating costs, and total costs of the fuel cell system are higher than the ICE APU alternative. In general, fuel cell systems continue to be more expensive than conventional alternatives on a capital cost basis. However, they are more cost effective on an operations, maintenance, and fuel consumption basis. Additionally, both the fuel cell and ICE APU maintain higher cost effectiveness than the alternative of engine idling; idling costs are based primarily on fuel prices (85%), which regularly suffer from high market cost fluctuation.

In order to make fuel cells more competitive with alternatives for larger market penetration, there is continued need to invest in research and development programs to bring down the cost of fuel cell systems and associated specialty BOP components.

10 Conclusions

This section provides a summary of the APU fuel cell system costs and resulting conclusions.

10.1 System Cost Summary

A high level summary of the final costs is shown below and emphasizes that the balance of plant dominates the final cost; at most it is estimated to account for 85% of the final cost before markup at high production volumes. In all sizes and production rates analyzed, the balance of plant was responsible for no less than 72% of the pre-markup price. Overall the final cost is analyzed in four distinct categories: the capital cost of manufacturing equipment, the direct cost of material and assembly of the stack, the expense of balance of plant hardware, and the final cost of complete system assembly and testing it. Anticipated scrap is also captured in the stack manufacturing cost.

Table 10-1. 1 kW APU SOFC System per Unit Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$590	$511	$481	$473
Stack manufacturing capital cost	$4,757	$495	$69	$43
Balance of plant	$9,597	$8,204	$7,383	$7,383
System assembly, test, and conditioning	$475	$451	$448	$448
Total system cost, pre-markup	$15,419	$9,661	$8,381	$8,347
System cost per net KW, pre-markup	$15,419	$9,661	$8,381	$8,347
Sales markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	$23,129	$14,491	$12,571	$12,520
System cost per net KW, with markup	$23,129	$14,491	$12,571	$12,520

A sales markup of 50% was integrated at the end and is called out separately in Tables 10-1 and 10-2. At high production volumes, the final ticket price is estimated to be $12,520 per net kW for a 1 kW APU SOFC system. This price decreases nearly 75% per kW for a 5 kW system. For a visual representation of the cost breakdown pre-markup, refer to the concluding pie charts.

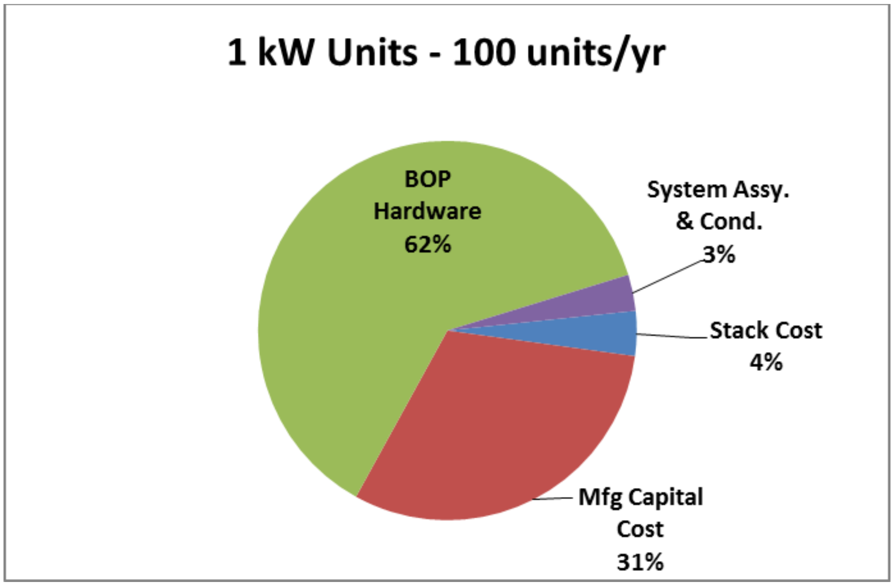


Figure 10-1. Distribution of Costs for 1 kW System (100 units/yr)

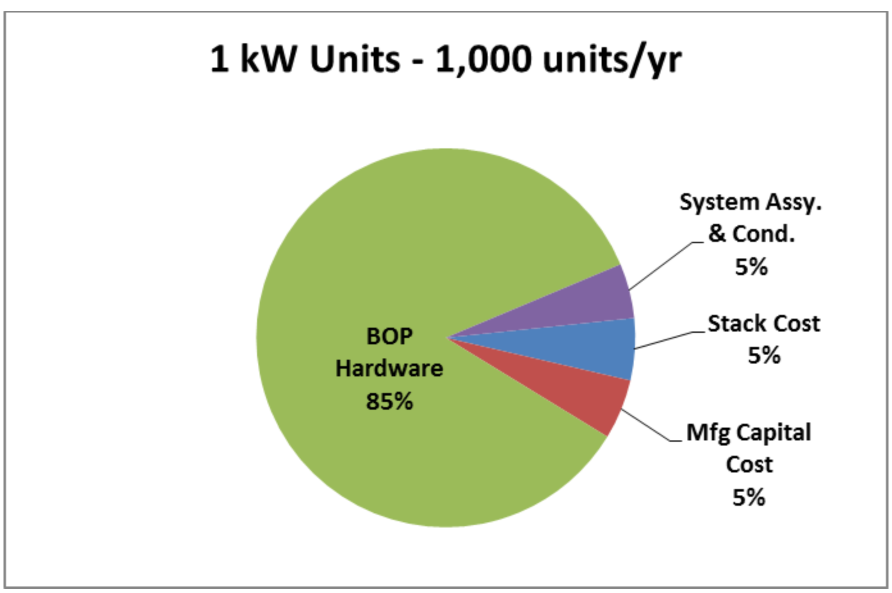


Figure 10-2. Distribution of Costs for 1 kW System (1,000 units/yr)

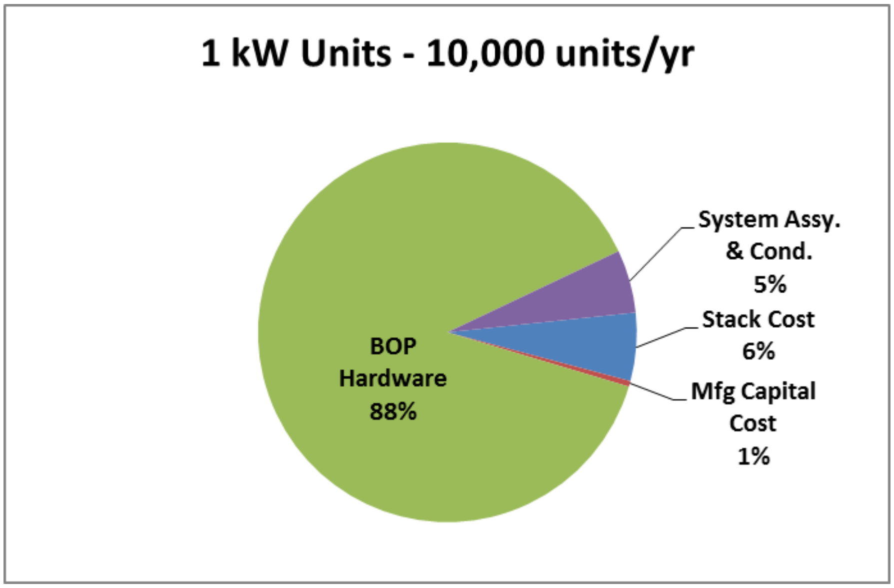


Figure 10-3. Distribution of Costs for 1 kW System (10,000 units/yr)

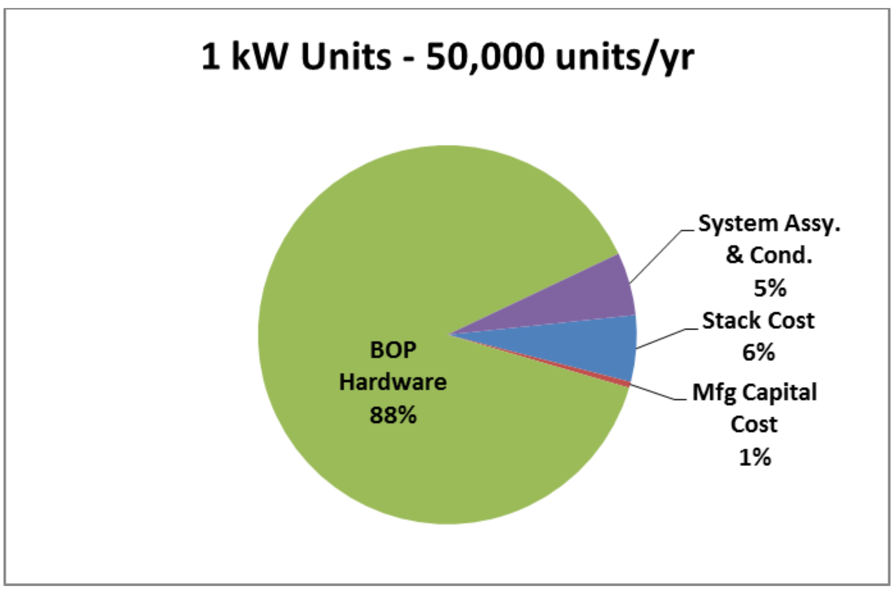


Figure 10-4. Distribution of Costs for 1 kW System (50,000 units/yr)

Table 10-2. 5 kW APU SOFC System Per Unit Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$1,476	$1,327	$1,267	$1,257
Stack manufacturing capital cost	$4,757	$495	$82	$73
Balance of plant	$11,323	$9,802	$8,738	$8,738
System assembly, test, and conditioning	$481	$456	$454	$454
Total system cost, pre-markup	**$18,037**	**$12,080**	**$10,541**	**$10,522**
System cost per net KW, pre-markup	**$3,607**	**$2,416**	**$2,108**	**$2,104**
Sales markup	50.00%	50.00%	50.00%	50.00%
Total system cost, with markup	**$27,056**	**$18,120**	**$15,812**	**$15,783**
System cost per net KW, with markup	**$5,411**	**$3,624**	**$3,162**	**$3,156**

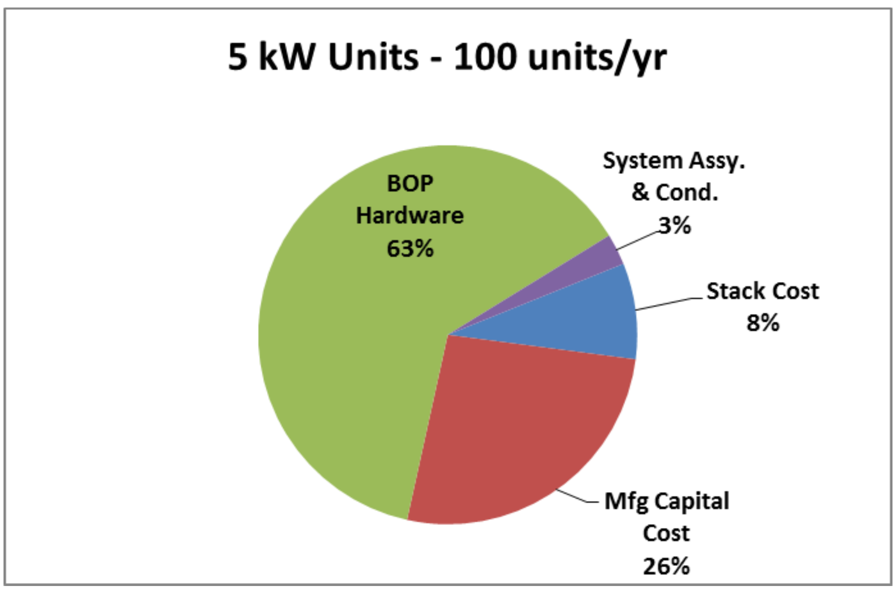


Figure 10-5. Distribution of Costs for 5 kW System (100 units/yr)

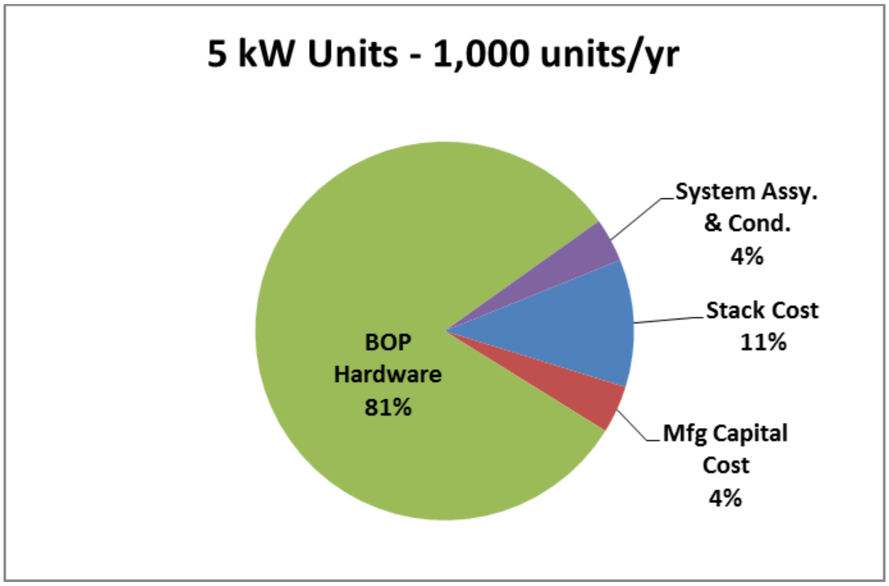


Figure 10-6. Distribution of Costs for 5 kW System (1,000 units/yr)

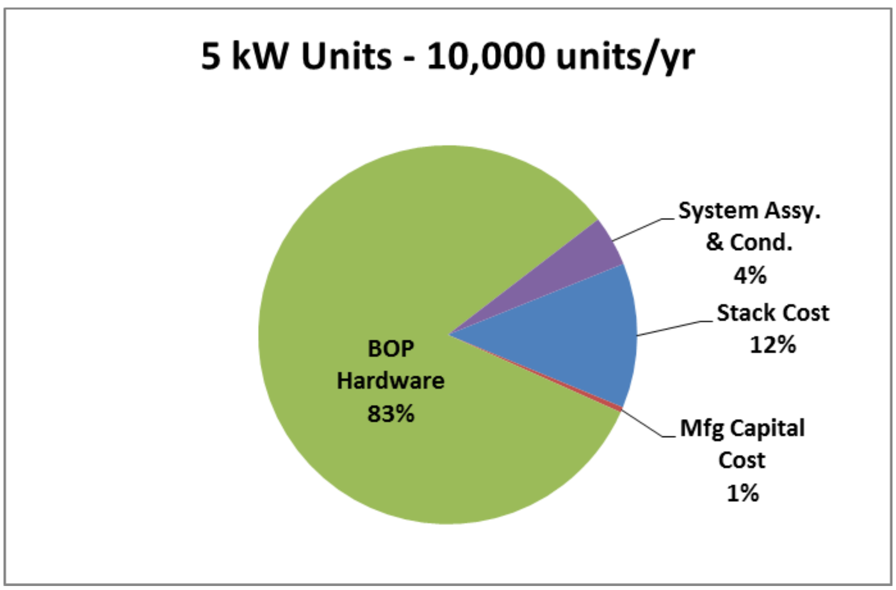


Figure 10-7. Distribution of Costs for 5 kW System (10,000 units/yr)

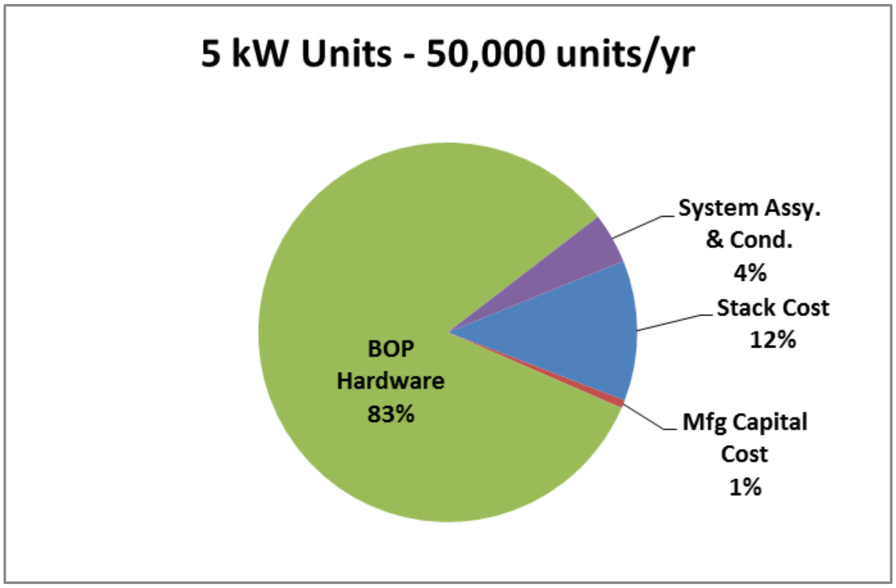


Figure 10-8. Distribution of Costs for 5 kW System (50,000 units/yr)

10.2 Results

The primary driver of overall APU system cost is the cost of BOP hardware; specifically, the DC/DC converter, heat exchangers, and air blowers make up around 60% of the total BOP cost. The stack cost is most sensitive to change in metal components, as the quantity of high temperature steel makes up the bulk of the stack cost.

Production volume considered in this report has negligible effect on stack cost, due to the fact that commodity material costs are fairly constant across the range of purchased material quantities. Stainless steel is generally purchased at market spot price. Commodity material (e.g., steel and ceramics) markets are generally mature with price points fairly level over all but the smallest purchase quantities.

The manufacturing costs are also constrained to a lower cost bound by the material processing requirements; i.e., regardless of the volume being produced, the time required to produce each part is the same. For example, the screen printing operation is limited by the maximum allowable squeegee speed of 25 mm/sec, plus the 3-hour post-application kiln-firing operation. In addition, each part is subject to two 3-hour sintering operations following deposition of the electrolyte and cathode layers, respectively. This places an upper limit on throughput, and a corresponding lower limit on manufacturing cost, which is a function of the machine time required in producing each part.

APPENDIX A

Appendix A – Stack Manufacturing Process and Cost Assumptions

A.1 Ceramic Slurry Production Process

Model Approach

- Ceramic slurry preparation operation
    - Machine setup labor cost based on input labor time; default = 1 hour
    - Compute required batch size based on part batch size and ceramic layer thickness
    - Compute ceramic slurry material cost
    - Compute ceramic slurry processing cost based on material handling time and batch milling time
    - Compute ceramic slurry cost per part

Process Flow

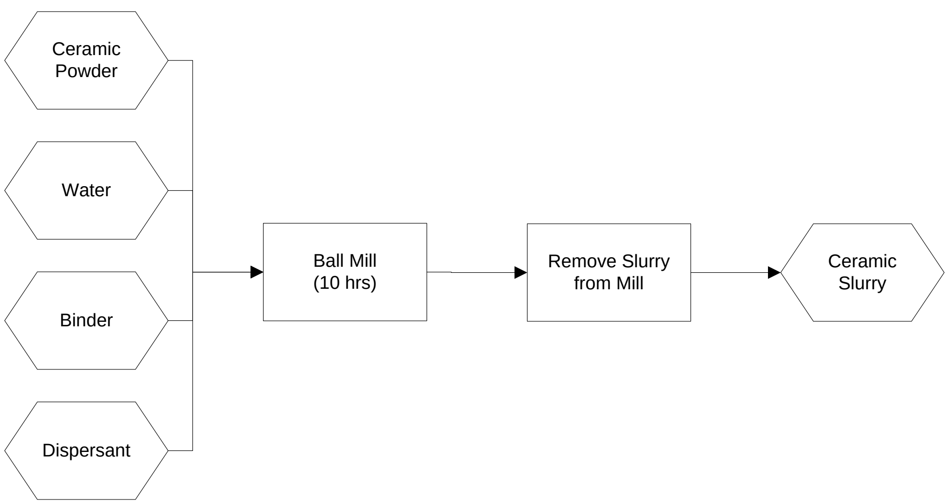


Figure A-1. Ceramic Slurry Production Process

Background

The composition of typical SOFC ceramic slurries used in industry is not directly reported, and fundamental work seems to be continuing in the area of ceramic powder characterization.

In the book Modern Ceramics Engineering (Richardson, 2006) list a typical solvent based slurry as:

- 70 wt% ceramic powder
- 14 wt% organic solvent (MEK/EtOH)
- 9 wt% binder (ethyl methacrylate)
- 1 wt% dispersant (fish oil)
- 6 wt% plasticizer (BBP/PEG)

In their study of sintering and deformation, Cologna (2010), et al, report using a water-based slurry in tape casting experiments as follows:

Electrolyte: blade gap = 30 µm; dry thickness = 12 ± 2 µm; 60% reduction
- 59 wt% YSZ (8% mol)
- 14 wt% water
- 26 wt% binder (Dow Duramax B-1000/B-1014)
- 2 wt% dispersant (ammonium polyacrylate)

Anode: blade gap = 500 µm; dry thickness = 270 ± 5 µm; 46% reduction
- 26 wt% YSZ (8% mol)
- 37 wt% NiO
- 12 wt% water
- 24 wt% binder
- 1 wt% dispersant

Cologna's values are consistent with general "rule-of-thumb" thickness reduction of 50% seen on several web sites and used on some technical papers. Therefore, for cost purposes, we will assume that wet ceramic deposition will be twice the thickness of the required final ceramic layer thickness.

Preliminary Analysis

Anode Batch Volume

Slurry batch volume depends on the part size, casting width, and ceramic layer thickness.

The cells for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2

5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

Material densities for the anode slurry components are as follows:
- ρ(YSZ) = 6.1 g/cm^3
- ρ(NiO) = 6.7 g/cm^3
- ρ(water) = 1.0 g/cm^3
- ρ(binder) = 1.05 g/cm^3
- ρ(dispersant) = 1.16 g/cm^3

Based on the slurry composition as specified above, 100 grams of wet slurry has a volume of:

$$v = (26/6.1) + (37/6.7) + (12/1.0) + (25/1.05) + (1/1.16) = 45.50 \text{ cm}^3$$

Yielding a wet slurry density of:

ρ(wet slurry) = (100/45.50) = 2.20 g/cm^3 = 2200 kg/m^3

The required dried depth of 250 microns required a deposited wet depth of 500 microns. The weight of slurry material required per part is:

1 kW: Wet slurry weight = 2.2 g/cm^3 $\times$ (488.48 $\times$ 0.05) cm^3 $\times$ 0.001 kg/g = 0.0537 kg/part

5 kW: Wet slurry weight = 2.2 g/cm^3 $\times$ (821.86 $\times$ 0.05) cm^3 $\times$ 0.001 kg/g = 0.0903 kg/part

Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 cells, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

Slurry batch size = 3,750 parts $\times$ 0.0537 kg/part = 201.4 kg

The 5 kW stack requires 38 cells, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Slurry batch size = 9,500 parts $\times$ 0.0903 kg/part = 857.9 kg

Anode Ceramic Slurry Material Cost

Material cost of the anode slurry is calculated using the weight percents of the slurry constituents multiplied by the raw material cost to determine a cost per kilogram. Costs for ceramic constituents in bulk supply are difficult to obtain. Bulk costs for binder and dispersant were obtained from alibaba.com in November, 2012. The cost of DI water is based on distillation costs from www.apswater.com in September, 2012. Summarizing:

- YSZ = $35/kg
- NiO = $32/kg
- Water = $0.11/kg
- Binder = $2.5/kg
- Dispersant = $1.27/kg

The raw material cost of the slurry is:

Raw material cost = (0.26 $\times$ 35) + (0.37 $\times$ 32) + (0.12 $\times$ 0.11) + (0.24 $\times$ 2.5) + (0.01 $\times$ 1.27)
Raw material cost = $21.566/kg

The cost per part would be:

1 kW: Raw material cost/part = $21.566/kg $\times$ 0.0537 kg/part = $1.158/part
5 kW: Raw material cost/part = $21.566/kg $\times$ 0.0903 kg/part = $1.947/part

Anode Ceramic Slurry Processing Cost

The first step is to weigh the materials out and place them in the mill. We will assume a manual process consisting of a measurement step and a material handling step. The BDI DFMA™ software contains an analogous operation for off-line precision measurement with a default value of 17.4 seconds for the measurement, and a minimum of 4 seconds for material handling. The slurry is made up of 5 materials, so that total handling time for material preparation can be estimated as:

$$\text{Material prep time} = 5 \times 21.4 \text{ sec} = 107 \text{ sec} = 1.8 \text{ minutes} = 0.03 \text{ hours}$$

The primary cost for operating the ball mill is the energy input to the motor running the mill. Some studies have looked into the cost of operating large ball mills used for cement and powder metallurgy material processing, where the target parameter is the amount of energy required to process a given amount of material, usually expressed in kW-hr/ton. The calculations are complex owing to the large number of inputs to the calculations.

In "Technical Notes 8, Grinding," R. P. King develops a relationship based on fundamental physical models of ball mill processing to determine mill power based on mill diameter, assuming that the length is twice the diameter, and that fairly standard values for loading apply. He presents a log-log plot showing that a mill with a diameter of 1 meter will consume about 10 kW of power, where a mill with a diameter of 2 meters consumes about 100 kW. These two values yield the equation:

$$\text{Power} = 10d^{3.32} \text{ kW}$$

His values assume a 35% volumetric loading ratio, giving a total charge volume of:

$$\text{Charge volume} = (\pi \times d^2 / 4) \times 2d \times 0.35 = 0.175\,\pi\, d^3 \text{ m}^3$$

In addition, he assumes that the volume of milling balls represents 10% of the total charge volume. Therefore, assuming 90% of the charge volume is slurry material, we can state that:

$$\text{Slurry volume} = 1.11 \times (\text{Slurry weight (kg)} / \text{Slurry density (kg/ m}^3)) = 0.175\,\pi\, d^3$$

Solving for d:

$$d = (2.02 \times (\text{Slurry weight (kg)} / \text{Slurry density (kg/ m}^3)))^{1/3}$$

To compute the power required to process a batch of slurry with a density of 2200 kg/m^3, we find the theoretical diameter of the fully loaded mill as:

$$1 \text{ kW: } d = (2.02 \times 201.4 \text{ kg} / 2200 \text{ kg/ m}^3)^{1/3} = 0.571 \text{ meters}$$
$$5 \text{ kW: } d = (2.02 \times 857.9 \text{ kg} / 2200 \text{ kg/ m}^3)^{1/3} = 0.924 \text{ meters}$$

Plugging the theoretical diameter into the power equation we have:

1 kW: Power = $10 \times (0.571)^{3.32} = 1.56$ kW
5 kW: Power = $10 \times (0.924)^{3.32} = 7.69$kW

Assuming an energy cost of \$0.07/kW-hr and a milling time of 10 hours, the energy cost of powering the mill per part is:

1 kW: Power cost = $0.07 \times 1.56 \times 10 / 3750 = \$0.0003$
5 kW: Power cost = $0.07 \times 7.69 \times 10 / 9500 = \$0.0005$

Once process is complete, the slurry will need to be separated from the milling balls and transferred to the coating machine. While we presently have no information about this part of the process, one approach would be the use of a vacuum sieve (e.g., Farleygreene, Ltd. SM950 Sievmaster Vacu-siev) to remove and separate the slurry from the mill, and transfer the slurry to a transport container or directly to the coater reservoir.

ShopVac reports a sealed suction of 54 in-H_2O (13.4 kPa) for their 2 HP (1.5 kW) unit. Using an equivalent vacuum sieve with a 1.5" (0.038 m) diameter hose and 80% transfer efficiency, the flow rate is:

Flow rate = $0.8 \times (\pi \times (0.038)^2 / 4) \times (2 \times 13.4 / 850)^{1/2} = 0.00016$ m^3/sec

Since the slurry is forms 90% of the charge volume, the total charge volume of

Charge volume (m^3) = $1.11 \times$ (Slurry weight (kg) / Slurry density (kg/ m^3))
Charge volume (m^3) = $0.0013 \times$ Slurry weight

Therefore, the optimal time required to remove the charge volume is:

Material removal time (sec) = Charge volume / Flow rate = $8.1 \times$ Slurry weight

The optimal time to remove a batch of slurry from the mill would be:

1 kW: Material removal time = $8.1 \times 201.4 = 1631$ sec = 27.2 minutes = 0.453 hours
5 kW: Material removal time = $8.1 \times 857.9 = 6950$ sec = 116 minutes = 1.93 hours

We will estimate the total transfer time to remove the slurry from the mill and transfer it to the coater as twice the slurry removal time.

Assuming an overall plant efficiency of 85% for machine and labor time, the costs per part are:

Material processing labor cost = (Material prep time + Material removal time) $\times$ Labor rate)] / Overall plant efficiency / Batch size

1 kW: Material processing labor cost = (0.03 + 0.453) hours $\times$ \$45/hour)] / 0.85 / 3750 = \$0.007/part

5 kW: Material processing labor cost = (0.03 + 1.93) hours × \$45/hour)] / 0.85 / 9500 = \$0.011/part

Material processing machine cost = (Machine time) × Machine rate)] / Overall plant efficiency / Batch size

1 kW: Material processing machine cost = (10 hours × \$25/hour) / 0.85 / 3750 = \$0.078
5 kW: Material processing machine cost = (10 hours × \$25/hour) / 0.85 / 9500 = \$0.031

The total material cost per part before scrap allowance is:

Total material cost/part = Raw material cost + Labor cost + Machine cost + Energy Cost

1 kW: Total material cost/part = 1.158 + 0.0003 + 0.007 + 0.078 = \$1.243/part
5 kW: Total material cost/part = 1.947 + 0.0005 + 0.011 + 0.031 = \$1.990/part

Assuming a scrap rate of 3%, the total material cost per part is:

1 kW: Total material cost/part = \$1.243 / 0.97 = \$1.281/part
5 kW: Total material cost/part = \$\$1.990 / 0.97 = \$2.052/part

A.2 Ceramic Tape Casting Process

Model Approach

- Tooling Cost
  - Compute tooling cost
- Tape Casting
  - Compute labor cost for machine setup
  - Compute material cost for tape casting substrate
  - Compute casting speed/throughput
  - Compute machine and labor cost for tape casting operation
- Oven Drying
  - Compute drying time and dryer length
  - Compute radiant heater area
  - Compute heater energy cost based on energy watt density and energy cost

Process Flow

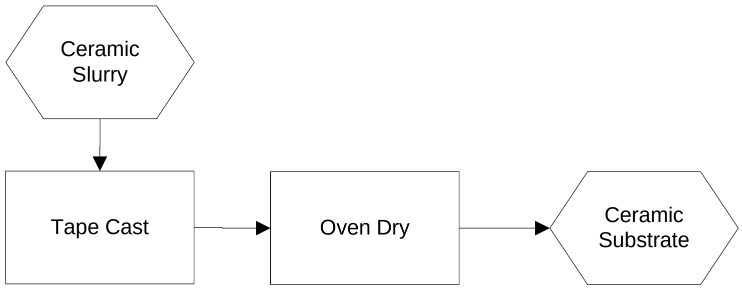


Figure A-2. Ceramic Tape Casting Process

Background

The tape casting process is well documented in literature by Richard Mistler and others. Personal communication with engineers at ESL Electroscience indicate that for thick tapes (over 100 microns) the pacing factor for line speed is drying time, which drives dryer length; in particular that tapes of 150 microns thickness are limited to approximately 1 m/min (1.6 cm/sec). ESL recommended casting multiple tapes of 100 micron thickness and laminating to the desired thickness. Technical literature, along with material specifications for DuPont™ GreenTape™ 951, indicates that the lamination is generally carried out as an iso-static hot pressing operation at 3000-3500 psi (20.7-24.1 MPa) at 70°C for 10-15 minutes.

Preliminary Analysis

The cells for this analysis will be working in two systems for which the total area size is:

1 kW Stack: 112 mm width $\times$ 224 mm length = 250.88 cm^2
5 kW Stack: 158 mm width $\times$ 317 mm length = 500.86 cm^2

The total part size includes a 30 mm margin, so that the overall part size for the anode support is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2
5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

To develop the analysis, we will assume that the screen printing operation is being used to apply the anode active layer, which has a finished depth of 15 microns. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 cells, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

The 5 kW stack requires 38 cells, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Tooling Cost

In a personal communication with Richard Mistler, author of Tape Casting: Theory and Practice (Wiley – American Ceramic Society, 2000), he estimates that a doctor blade for this application would cost approximately \$2,050 and would "last for years". Using 100,000 parts as a life approximation, the tooling cost per part is:

Tooling cost per part = \$2,050 / 100,000 parts = \$0.021/part

Tape Casting

Since the slurry cost is calculated separately, the material cost will consist of the cost of the tape casting carrier film. The carrier film is usually Mylar or polyethylene. For roll stock in 2 mil thickness, these materials cost approximately \$2.00/m^2 in bulk. Assuming that the casting width will be equal to the longest part dimension (i.e., the part length), the required casting length is determined by the part width as:

1 kW: Carrier length = (172 mm / 1000) × 3750 = 645 m
5 kW: Carrier length = (218 mm / 1000) × 9500 = 2071 m

Tape casting machine setup consists of loading and threading the casting substrate, and loading the ceramic slurry into the reservoir. For costing purposes, we will take the setup time as a user input and assume a value of 1 hour and overall plant efficiency of 85%. Bulk roll stock is available in 1000 meter lengths, so that the number of setups required to run a batch of parts is:

Number of setups = Roundup(Carrier length (m) / Roll length (m))

The setup cost per part is calculated as:

Setup cost per part = Number of setups × Setup time (hr) × Labor rate (\$/hr) / Parts per batch / Overall plant efficiency
1 kW: Setup cost per part = Roundup(645 / 1000) × 1 × 45 / 3750 / 0.85 = \$0.014/part
5 kW: Setup cost per part = Roundup(2071 / 1000) × 1 × 45 / 9500 / 0.85 = \$0.017/part

Allowing 25 mm casting margin on each side, the required minimum roll widths are:

1 kW: Minimum carrier width = 334 mm = 13.14 inches
5 kW: Minimum carrier width = 427 mm = 16.81 inches

Rolls commonly appear in 6 inch (152.4 mm) incremental widths, requiring an 18" (457.2 mm) roll width. The cost for carrier material per part is:

1 kW: Carrier material cost per part = (0.458 × 645) m^2 × \$2.00/m^2 / 3750 parts = \$0.157/part
5 kW: Carrier material cost per part = (0.458 × 2071) m^2 × \$2.00/m^2 / 9500 parts = \$0.200/part

Casting speed is limited by the slurry material properties, since running too fast can result in non-uniform deposition. In "Tape casting of high dielectric ceramic composite substrates for microelectronics applications," Tok, et.al., plotted experimental data relating maximum green tape thickness to casting speed, which shows a roughly exponential shape. Using the Excel function LOGEST for estimating an exponential curve fit produced the following relationship with maximum 3% error in the range of 150 – 300 microns:

$$\text{Casting speed (mm/sec)} = 157.18 \times 0.987^{\text{Green tape thickness (microns)}}$$

For a green tape thickness of 250 microns, the resulting casting speed is:

$$\text{Casting speed} = 157.18 \times 0.987^{250} = 5.97 \text{ mm/sec} = 0.358 \text{ m/min}$$

Part throughput is calculated as:

Throughput (parts/hour) = Casting speed (m/min) / Part width (m) * 60 min/hour
1 kW: Throughput = 0.358 / (172 / 1000) × 60 = 124.9 parts/hour
5 kW: Throughput = 0.358 / (218 / 1000) × 60 = 98.53 parts/hour

Machine cost per part is:

1 kW: Machine cost/part = $25.00/hour / 124.9 parts/hour = $0.200/part
5 kW: Machine cost/part = $25.00/hour / 98.53 parts/hour = $0.254/part

Assuming 1 operator per casting machine, the labor cost per part is:

1 kW: Labor cost/part = 1 × $45.00/hour / 124.9 parts/hour = $0.360/part
5 kW: Labor cost/part = 1 × $45.00/hour / 98.53 parts/hour = $0.457/part

Casting speed is also a function of required drying time and available dryer length. HED® International's PRO-CAST® series features systems ranging in length from 12 to 100 feet (3.66 to 30.5 meters).

Ceramic Slurry Drying

Following deposition, the ceramic slurry is dried, usually by means of a tunnel dryer positioned directly after the deposition step. The drying can be done by either radiant or convective heating. For the cost analysis, we will assume radiant (infrared) heating and compute the cost of drying by determining the required heater area.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler (Tape casting of ceramics, *Ceramic Processing Before Firing*, 1978) indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 l/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 l/min.

Previous analysis assumed that the anode slurry material was formulated as follows:

- 26 wt% YSZ (8% mol)
- 37 wt% NiO
- 12 wt% water
- 24 wt% binder (Dow Duramax B-1000/B-1014)
- 1 wt% dispersant

The binder consists of approximately 45% solids. Roughly estimating the volume of liquid per gram of slurry by multiplying the material density by the material weight percent:

$$\text{Liquid density} = (0.12 \times 1.0) + ((0.24 \times 0.55) \times 1.05) + (0.01 \times 1.16) = 0.270 \text{ g/cm}^3$$

The weight of liquid to be removed per unit area is a function of slurry thickness:

$$\text{Liquid removed per area} = 0.270 \text{ g/cm}^3 \times 0.05 \text{ cm} = 0.0135 \text{ g/cm}^2$$

At a rate of 2.0×10^{-5} g/cm^2-sec drying rate, the estimated drying time is:

$$\text{Drying time} = 0.0135 \text{ g/cm}^2 / 2.0\times10^{-5} \text{ g/cm}^2\text{-sec} = 675 \text{ sec} = 11.25 \text{ min}$$

At a casting speed of 0.35 m/min, the required dryer length is:

$$\text{Dryer length} = 0.358 \text{ m/min} \times 11.25 \text{ min} = 4.03 \text{ meters}$$

Infrared heating panels are generally sold with various energy watt densities and in standard sized units and assembled to provide the necessary heating area. Using the Casso Solar Type FB as an example, standard watt densities are 15 and 25 W/in^2 (23 and 39 kW/m^2) with standard width of 12" (0.305 m) and lengths in 12" increments up to 60" (1.524 m). They note that 25 W/in^2 corresponds to an emitter temperature of 880°C, and that the conversion efficiency of electrical power to usable radiant energy is up to 80%.

The theoretical required heater area is calculated as:

$$\text{Heater area} = \text{Dryer length (meters)} \times (\text{Part width (mm)} / 1000)$$

$$\text{1 kW: Heater area} = 4.03 \times (284 / 1000) = 1.14 \text{ m}^2$$
$$\text{5 kW: Heater area} = 4.03 \times (377 / 1000) = 1.52 \text{ m}^2$$

While the heater energy density will be taken as an input, the drying temperatures for the green tape are fairly moderate (150°C or less), so that the 23 kW/m^2 should be sufficient to maintain the drying area temperature. Using an energy cost of \$0.07/kW-hr, the hourly energy cost to power the heaters will be:

$$\text{1 kW: Heating cost/hour} = 1.14 \text{ m}^2 \times 23 \text{ kW/m}^2 \times \$0.07\text{/kW-hr} = \$1.84\text{/hour}$$
$$\text{5 kW: Heating cost/hour} = 1.52 \text{ m}^2 \times 23 \text{ kW/m}^2 \times \$0.07\text{/kW-hr} = \$2.45\text{/hour}$$

The process cost per part associated with the drying operation is calculated based on the throughput in part/hour, which is a function of substrate speed and part length as follows:

Heating cost/part = Heating cost/hour (\$/hr) × (Part length (mm) / 1000) / (Substrate speed (m/min) × 60 min/hr)

1 kW: Heating cost/part = 1.84 × (172 / 1000) / (0.35 × 60) = \$0.015/part
5 kW: Heating cost/part = 2.45 × (218 / 1000) / (0.35 × 60) = \$0.025/part

Note: While researching the tape casting process, the manufacturing specifications for the 1 kW parts were provided to HED International, a manufacturer of coaters, dryers, kilns and furnaces. They recommended their TCM-251M tape casting machine with 12" (300 mm) casting width and 25 foot (7.7 meter) casting length with counter-flow heated-air dryer. The total machine power rating is 24 kW, the bulk of which would be consumed by the drying system. This is consistent with our estimate of 25.76 for the 1 kW parts.

A.3 Anode Blanking Process

Model Approach

- Anode blanking operation
  - Machine setup labor cost based on number of setups required to process material and input labor time; default = 1 hour
  - Tooling cost based on die cutting length and die life
  - Press cost based on cutting force required and standard machine rate

Process Flow

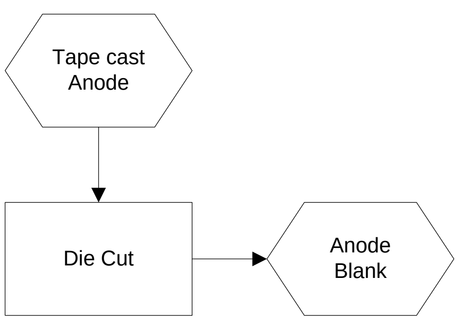


Figure A-3. Anode Blanking Process

Background

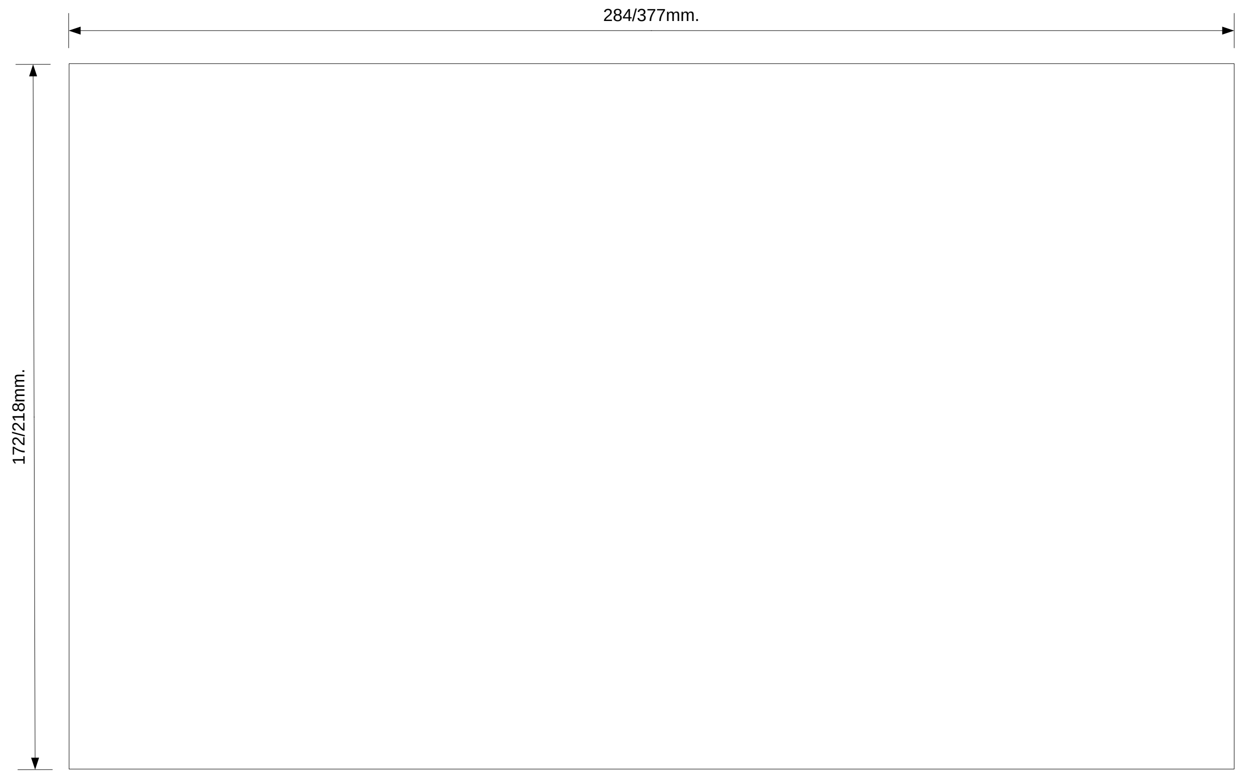
We will assume that the pre-fired anode tape has similar physical properties to those of elastomeric materials. The primary method for blanking elastomeric materials with standard features and tolerances is steel rule die cutting. The outline of the gasket is laid out and cut into a board. Strip steel is embedded into the board at a uniform height and mounted on a small stroke, fast acting press. The anode material is fed into the press where the steel rule die shears the material. The cutout areas of the blank are pushed out of the bulk material and the blanks stacked.

Preliminary Analysis
The blanked anodes for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2

5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

The layout of the cell blanks is shown below:



Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 interconnects, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

The 5 kW stack requires 38 interconnects, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Setup

Assuming a 1 hour setup time at a labor cost of \$45/hr and overall plant efficiency of 85%, the setup cost per part is:

1 kW: Setup cost = 1 hr × \$45/hr / 0.85 / 3,750 = \$0.014/part
5 kW: Setup cost = 1 hr × \$45/hr / 0.85 / 9,500 = \$0.006/part

Tooling

The primary factor contributing to steel rule die cost is the total cutting length of the die. The tape is assumed to be the width of the finished part, and we will assume a 4 cavity die cutter for the 5 kW anode size, giving an overall die size of approximately 400 mm by 900 mm fitting into a standard 0.5 meter by 1 meter platen. This same platen is capable of handling 5 cavities for the 1 kW anode size.

For the cutting configurations shown above, the cutting length (mm) is:

1 kW: Cutting length = 2 × (284 + 172) = 912 mm/part
5 kW: Cutting length = 2 × (377 + 218) = 1190 mm/part

A rough quote obtained from steel-rule-dies.com indicates that an approximate die tooling rate of \$0.04/mm applies for simple configurations.

Information obtained from Mag-Knight (www.mag-knight.com/diecutting/Steel_Rule_Dies.htm) indicates that dies used to cut softer materials have an expected life of about 30,000 hits. Given the abrasive nature of the ceramic materials used in the anode, we will assume a tooling life of approximately 2/3rds this value, or about 20,000 hits. Total tooling cost per part for a 2 cavity die can be calculated as:

Tooling cost = Number of cavities × Cutting length (mm) × Tooling rate / Tooling life
1 kW: Tooling cost = 5 cavities × 912 mm/part × \$0.04/mm / 20000 parts = \$0.009/part
5 kW: Tooling cost = 4 cavities × 1190 mm/part × \$0.04/mm / 20000 parts = \$0.010/part

Die Cutting

The primary energy input to run the press is hydraulic pump motor power. The total force required to cut the material is the total shear area (cutting length × material thickness) multiplied by the material shear strength. Assuming that the unfired anode material has the approximate consistency of high-density polyethylene (HDPE), we will use 23 N/mm^2 as the shear strength, giving the total required press force as:

Press force = Number of cavities × Cutting length (mm) × Material thickness (mm) × Shear strength (N/mm^2)
1 kW: Press force = 5 dies × 912 mm/die × 0.25 mm × 23 N/mm^2 = 26.22 kN = 2.63 tons

5 kW: Press force = 4 dies × 1190 mm/die × 0.25 mm × 23 N/mm^2 = 27.37 kN = 2.75 tons

A survey of 15 to 100 ton (150 – 1000 kN) fast-acting die cutting presses found that the motor power required to operate the press fell in the range of 0.015 – 0.025 kW/kN. Assuming a 50% capacity margin and using the upper end of the motor power rating, the required press energy input is:

Press energy = 27 kN × 1.5 × 0.025 kW/kN = 1.01 kW

The cost of energy usage to operate the press is calculated as:

Press energy rate = $0.07/kW-hr × 1.01 kW = $0.071/hr

Typical die cutting press speed ranges from 30 – 60 cycles/min (1800 – 3600 cycles/hour). Assuming the slower speed, the time to process a part is calculated as

Part cycle time = 1 / (Parts per cycle × Cycles per hour)
1 kW: Part cycle time = 1 / (5 parts/cycle × 1800 cycle/hour) = 0.00011 hours
5 kW: Part cycle time = 1 / (4 parts/cycle × 1800 cycle/hour) = 0.00014 hours

The total machine cost per part is calculated as the press energy cost ($/hr)) plus the standard machine cost ($/hr) multiplied by the batch processing time and divided by the overall plant efficiency and batch size:

1 kW: Machine cost = ((0.00011 hr/part+ $25/hr) / 0.85 = $0.003/part
5 kW: Machine cost = ((0.00014 hr/part+ $25/hr) / 0.85 = $0.004/part

The total labor cost per part is calculated as the number of operators per machine multiplied by the labor rate ($/hr) and batch processing time and divided by the overall plant efficiency and batch size:

1 kW: Labor cost = (1 operator × $45/hr × 0.00011 hr/part) / 0.85 = $0.006/part
5 kW: Labor cost = (1 operator × $45/hr × 0.00014 hr/part) / 0.85 = $0.007/part

A.4 Ceramic Screen Printing Process

Model Approach

- Screen Preparation
    - Compute tooling cost
    - Compute labor cost for screen cleaning
    - Compute labor and material cost for emulsion coating based on required ceramic layer thickness
    - Compute energy, machine and labor cost for masking and emulsion exposure

    - Compute energy, machine and labor cost for emulsion rinse and post-cure
- Screen Printing
    - Compute labor cost for machine setup
    - Compute labor cost for substrate load/unload
    - Compute machine cost for screen printing operation
- Oven Drying
    - Compute required heater area based on drying time and required conveyor speed
    - Compute heater energy cost based on energy watt density and energy cost

Process Flow

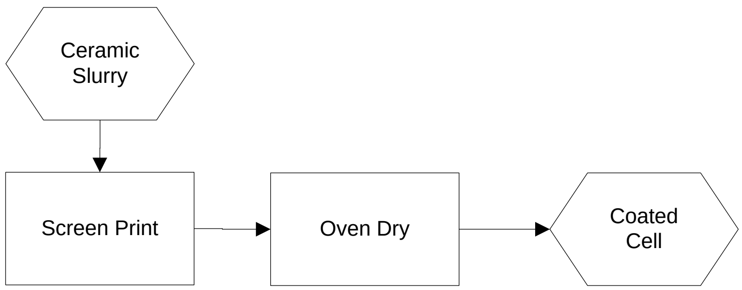


Figure A-4. Ceramic Screen Printing Process

Background

The mechanics of the screen preparation and printing process are described in several on-line sources, as well as a series of instructional videos produced by Cat Spit Productions found on YouTube. The calculations used for the screen preparation process were based on material and process specifications for Ulano QT-THIX emulsion and the article "Screen Coating Techniques" available from emulsion manufacturer Kiwo at http://www.kiwo.com/Articles. Technical details of the printing process were based on the article "Screen and Stencil Printing" available at http://www.ami.ac.uk/courses/topics/0222_print/index.html, and "The Basics of Printing Thick Film Inks" available at from DuPont Microcircuit Materials at http://www2.dupont.com/MCM/en_US/techtip/basics.html.

Preliminary Analysis

The cells for this analysis will be working in two systems for which the deposition area size is:

1 kW Stack: 112 mm width × 224 mm length = 250.88 cm^2
5 kW Stack: 158 mm width × 317 mm length = 500.86 cm^2

The total part size includes a 30 mm margin, so that the overall part size is:

1 kW Stack: 172 mm width × 284 mm length = 488.48 cm^2
5 kW Stack: 218 mm width × 377 mm length = 821.86 cm^2

To develop the analysis, we will assume that the screen printing operation is being used to apply the anode active layer, which has a finished depth of 15 microns. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 cells, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

The 5 kW stack requires 38 cells, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Screen Tooling Cost

Screen size is determined based on pattern area. Dupont recommends a squeegee length of 10-20 mm beyond the pattern area (part width) on both sides, and squeegee travel of 50-80 mm beyond the pattern area (part length) on both ends. Bopp, a printing mesh manufacturer, recommends a screen width of 3 times the squeegee width and screen length of 2 times the squeegee travel. The minimum screen size can be calculated as:

Screen width = 3 $\times$ (Part width + 20)
Screen length = 2 $\times$ (Part length + 100)

For the two part sizes, the screen sizes are:

1 kW: Screen width = 3 $\times$ (112 + 20) = 396 mm
1 kW: Screen length = 2 $\times$ (224 + 100) = 648 mm
1 kW: Screen area = 396 $\times$ 648 = 2566 cm^2
5 kW: Screen width = 3 $\times$ (158 + 20) = 534 mm
5 kW: Screen length = 2 $\times$ (317 + 100) = 834 mm
5 kW: Screen area = 534 $\times$ 834 = 4454 cm^2

The two primary wear items are the screen and the squeegee. Atlas screen supply company quotes triple durometer squeegee material for \$2.05/inch (\$0.81/cm). Squeegee cost is:

1 kW: Squeegee cost = \$0.81 $\times$ 13.2 = \$10.69
5 kW: Squeegee cost = \$0.81 $\times$ 17.8 = \$14.42

AMI indicates that polymer squeegees may be changed daily in high volume production applications, indicating a useful life of around 5000 - 6000 parts.

Web quotes for fine mesh precision metal screens in 24” x 30” size ranged from \$50 to \$100, equating to about \$0.02/cm^2, giving estimated screen costs of:

1 kW: Screen cost = \$0.02 $\times$ 2566 = \$51.32
5 kW: Screen cost = \$0.02 $\times$ 4454 = \$89.09

AMI reports screen lives between 5000 and 50,000 cycles. Given the nature of the ceramic inks used, we will assume the lower value of 5000 cycles. Total tooling cost per part based on a life of 5000 cycles for both the squeegee and screen is:

1 kW: Tooling cost = (\$10.69 + 51.32) / 5000 = \$0.012
5 kW: Tooling cost = (\$14.42 + 89.09) / 5000 = \$0.021

Screen Preparation

Screen preparation is a manual process that consists of cleaning, emulsion coating, emulsion masking and exposure to high intensity light, emulsion rinsing and post cure using high intensity light. The primary cost component will be the labor involved in handling and coating the screen. An empirical formula developed by Boothroyd-Dewhurst calculates a quantity called part girth, then calculates a theoretical total handling time (both load and unload) with a minimum value of 4 seconds. Adapting the formula for dimensions in millimeters and handling of large, light-weight parts, the handling time is calculated as follows:

Part girth = Part length + Part width + Part depth
Handling time = Max((0.3 × (Part girth / 25.4) - 4.6), 4)

Common screen frames are 1 inch (25.4 mm) thick, so that the handling time for each size screen is:

1 kW: Handling time = Max((0.3 × (1069.4 / 25.4) - 4.6), 4) = 8.0 sec
5 kW: Handling time = Max((0.3 × (1393.4 / 25.4) - 4.6), 4) = 11.9 sec

Cleaning is assumed to be accomplished by brushing the screen mesh and spray rinsing with water. The time to accomplish the tasks will consist of a tool acquisition time (e.g., brush, hose) and operation time. The general default time for acquisition of tools within easy reach is 3 seconds, and is applicable to a wash station set-up. Brush and rinse operation time will depend on the treatment area. No general area-based guidelines could be found, so we will assume that the operation time per screen side can be estimated using an adaptation of the formula as the total handling time. The calculation for a combination clean and rinse operation for both sides of a screen becomes:

Cleaning time = 4 × (3 + Handling time)
1 kW: Cleaning time = 4 × (3 + 8.0) = 44.0 sec
5 kW: Cleaning time = 4 × (3 + 11.9) = 59.6 sec

The emulsion coating is applied with a hand-held trough coater with width equal to the screen width. This allows the emulsion to be applied in one fluid motion from the bottom to the top of the screen. Observations of video recordings of the process indicate that a single coat can be applied to a 1 meter length in approximately 5 seconds. Using 3 seconds for tool acquisition, the time to apply a single coat can be estimated as:

Emulsion application time = 3 + (Screen length / 1000) × 5
1 kW: Emulsion application time = 3 + (648 / 1000) × 5 = 6.24 sec
5 kW: Emulsion application time = 3 + (834 / 1000) × 5 = 7.17 sec

The number of emulsion coats depends on the desired coating depth. Dupont suggests that fine mesh screens provide a dry print depth for thick film inks of approximately 16 microns. Further reductions in film thickness achieved through calendar rolling of the screen. Kiwo recommends 2 coats of emulsion on the squeegee side of the screen, followed by at least one coat up to as many coats on the print side as necessary to provide the proper coating depth. The number of emulsion coats can be estimated as:

Number of coats = 3 + Max((Coating depth – 16), 0)
1 kW & 5 kW: Number of coats = 3 + Max((15 – 16), 0) = 3 coats

Screens are air dried for about 1 hour following coating. Consequently, no additional labor time is accumulated for the drying operation. Total emulsion coating time is calculated as:

> Emulsion coating time = Number of coats × (Emulsion application time + Handling time)
> 1 kW: Emulsion coating time = 3 × (6.24 + 8.0) = 42.72 sec
> 5 kW: Emulsion coating time = 3 × (7.17 + 11.9) = 57.21 sec

The emulsion is developed by applying the pattern mask and exposing the coated screen to 4500 watt light for a period equal to approximately 1 minute per 1 micron of emulsion depth and a minimum of 15 minutes. Assuming approximately 4 seconds to place the mask, the handling time for the 1 kW and 5 kW parts will be 12.0 and 15.9 seconds respectively. The cost of powering the light source can be calculated as:

> Exposure power cost = Energy rate ($/kW-hr) × ((15 + Max((Coating depth – 15), 0) / 60) hrs. × 4.5 kW
> 1 kW & 5 kW: Exposure power cost = 0.07 × (15 / 60) × 4.5 = $0.008

The unexposed emulsion is rinsed from the screen in a manner similar to the cleaning step, air dried, and re-exposed to the light source to harden the emulsion coating on the squeegee side of the screen. Using the cost equations developed previously:

> Rinsing time = 2 × (3 + Handling time)
> 1 kW: Rinsing time = 2 × (3 + 8.0) = 22.0 sec
> 5 kW: Rinsing time = 2 × (3 + 11.9) = 29.8 sec
> 1 kW & 5 kW: Post-cure power cost = 0.07 × (15 / 60) × 4.5 = $0.008

Summarizing screen preparation by step:

	1 kW		5 kW	
	Labor time	Energy Cost	Labor time	Energy Cost
Cleaning	44.00		59.60	
Coating	42.72		57.21	
Exposure	12.00	$0.008	15.90	$0.008
Rinsing	22.00		29.80	
Post-cure	8.00	$0.008	11.90	$0.008
Total	128.72	$0.016	174.41	$0.016

Total labor cost per part for screen preparation is:

> Labor cost per part = Labor time (hrs) × Labor rate ($/hr) / Overall plant efficiency (%) / Screen life (parts)
> 1 kW: Labor cost per part = (128.72 / 3600) × 45 / 0.85 / 5000 < $0.001/part
> 5 kW: Labor cost per part = (174.41 / 3600) × 45 / 0.85 / 5000 < $0.001/part

Energy cost and labor cost for screen preparation on a per part basis are negligible.

Screen Printing

The screen printing operation consists of a part load/unload, which may be manual or robotic, but will be driven by overall part size. Using the handling time formula developed previously, the load/unload time is:

1 kW: Handling time = Max((0.3 × ((172 + 284 + 1) / 25.4) - 4.6), 4) = 4.0 sec
5 kW: Handling time = Max((0.3 × ((218 + 377 + 1) / 25.4) - 4.6), 4) = 4.0 sec

The time to perform the printing operation is a function of the flood blade speed, which can be estimated to move at 4 times the squeegee speed. Setting L to the squeegee travel length and S to the squeegee speed:

Substrate coating time = (L/S) + (L/4S) = 1.25 × (L/S)

Observations of SOFC screen printing operations suggest that the squeegee speed is approximately 25 mm/sec. Using these values, the time to coat the substrate is:

1 kW: Substrate coating time = 1.25 × (324 / 25) = 16.2 sec
5 kW: Substrate coating time = 1.25 × (417 / 25) = 20.85 sec

Assuming manual handling and one operator per station, the labor and machine costs for the screen printing operation are:

1 kW: Labor cost per part = ((16.2 + 4.0) / 3600) × 45 / 0.85 = $0.297/part
1 kW: Machine cost per part = ((16.2 + 4.0) / 3600) × 25 / 0.85 = $0.165/part
5 kW: Labor cost per part = ((20.85 + 4.0) / 3600) × 45 / 0.85 = $0.365/part
5 kW: Machine cost per part = ((20.85 + 4.0) / 3600) × 25 / 0.85 = $0.203/part

Ceramic Slurry Drying

Following deposition, the ceramic slurry is dried, usually by means of a tunnel dryer positioned directly after the deposition step. The drying can be done by either radiant or convective heating. For the cost analysis, we will assume radiant (infrared) heating and compute the cost of drying by determining the required heater area based on throughput and the drying time.

Drying time is a function of the evaporation rate of the solvent and is inversely and exponentially proportional to the coating thickness. Experiments conducted by Mistler (Tape casting of ceramics, *Ceramic Processing Before Firing*, 1978) indicate drying rates of 1.35×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 2 l/min, and 2.22×10^{-5} g/cm^2-sec at room temperature for an air flow rate of 75 l/min.

Previous analysis assumed that the screen printed slurry material was formulated with aqueous components as follows:

- 12 wt% water
- 24 wt% binder (Dow Duramax B-1000/B-1014)
- 1 wt% dispersant

The binder consists of approximately 45% solids. Roughly estimating the volume of liquid per gram of slurry by multiplying the material density by the material weight percent:

$$\text{Liquid density} = (0.12 \times 1.0) + ((0.24 \times 0.55) \times 1.05) + (0.01 \times 1.16) = 0.270\ \text{g/cm}^3$$

The weight of liquid to be removed per unit area is a function of slurry thickness. As with tape casting, we assume a 50% thickness reduction after drying. Using the anode active layer (15 micron green thickness; 30 micron wet thickness) as an example:

$$\text{Liquid removed per area} = 0.270\ \text{g/cm}^3 \times 0.003\ \text{cm} = 0.0008\ \text{g/cm}^2$$

At a rate of 2.0×10^{-5} g/cm^2-sec drying rate, the estimated drying time is:

$$\text{Drying time} = 0.0008\ \text{g/cm}^2 / 2.0\times10^{-5}\ \text{g/cm}^2\text{-sec} = 40.5\ \text{sec} = 0.675\ \text{min}$$

The conveyor speed is a function of part throughput and belt length required to transport the part. Throughput is simply the inverse of the cycle time. Using the results above, the throughput is:

1 kW: Throughput = 1 / (4 + 16.2) = 0.0495 parts/sec = 2.97 parts/min
5 kW: Throughput = 1 / (4 + 20.85) = 0.0402 parts/sec = 2.41 parts/min

Assuming a 50 mm gap between parts on the belt, the conveyor speed can be calculated as:

Conveyor speed = Belt length per part (mm/part) / (Throughput (parts/min)
1 kW: Conveyor speed = (112 + 50) / 2.97 = 54.5 mm/min = 0.055 m/min
5 kW: Conveyor speed = (158 + 50) / 2.41 = 86.3 mm/min = 0.086 m/min

Infrared heating panels are generally sold with various energy watt densities and in standard sized units and assembled to provide the necessary heating area. Using the Casso Solar Type FB as an example, standard watt densities are 15 and 25 W/in^2 (23 and 39 kW/m^2) with standard width of 12" (0.305 m) and lengths in 12" increments up to 60" (1.524 m). They note that 25 W/in^2 corresponds to an emitter temperature of 880°C, and that the conversion efficiency of electrical power to usable radiant energy is up to 80%.

For a drying time of 0.675 minutes, the required heater area is:

Heater area = Drying time (min) $\times$ Conveyor speed (m/min) $\times$ (Belt length per part (mm) / 1000)
1 kW: Heater area = $0.675 \times 0.055 \times (162 / 1000) = 0.006$ m^2
5 kW: Heater area = $0.675 \times 0.086 \times (208 / 1000) = 0.012$ m^2

While the heater energy density will be taken as an input, the drying temperatures for the ceramic slurry are fairly moderate (150°C or less), so that the 23 kW/m^2 should be sufficient to maintain the drying area temperature. Using an energy cost of \$0.07/kW-hr, the hourly energy cost to power the heaters will be:

1 kW: Heating cost/hour = 0.006 m^2 $\times$ 23 kW/m^2 $\times$ \$0.07/kW-hr = \$0.010/hour
5 kW: Heating cost/hour = 0.012 m^2 $\times$ 23 kW/m^2 $\times$ \$0.07/kW-hr = \$0.019/hour

The heating cost per part is:

1 kW: Heating cost/part = \$0.011/hour $\times$ (23.2 sec/part / 3600 sec/hour) < \$0.001/part

5 kW: Heating cost/part = \$0.032/hour × (27.85 sec/part / 3600 sec/hour) < \$0.001/part

The machine cost per part associated with the drying operation is:

1 kW: Machine cost/part = \$25.00/hour / (2.97 parts/min * 60 min/hour) / 0.85 = \$0.165/part
5 kW: Machine cost/part = \$25.00/hour × (2.41 parts/min * 60 min/hour) / 0.85 = \$0.203/part

A.5 Kiln Firing Process

Model Approach

- Kiln Firing
    - Part handling time labor cost based on part size per BDI formula and throughput; 4 second minimum
    - Process cost based on oven energy cost plus standard machine rate

Process Flow

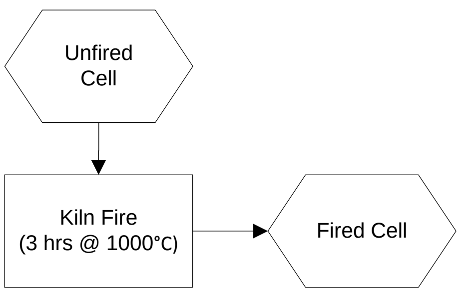


Figure A-5. Kiln Firing Process

Preliminary Analysis

The cells for this analysis will be working in two systems for which the total part size is:

1 kW Stack: 172 mm width × 284 mm length = 488.48 cm^2
5 kW Stack: 218 mm width × 377 mm length = 821.86 cm^2

To develop the analysis, we will assume that the screen printing operation is being used to apply the anode active layer, which has a finished depth of 15 microns. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 cells, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack × 250 stacks = 3,750 parts

The 5 kW stack requires 38 cells, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack × 250 stacks = 9,500 parts

Kiln firing cost

The SOFC process calls for kiln firing at 1000°C (1832°F) for 3 hours after the part reaches temperature. For a batch type oven, assume a single setup operation requiring 1 operator per batch of parts. The setup cost per part is:

1 kW: Setup cost per part = 1 hour × \$45/hour / 3,750 parts / 0.85 = \$0.014/part
5 kW: Setup cost per part = 1 hour × \$45/hour / 9,500 parts / 0.85 = \$0.006/part

Assuming a batch type industrial kiln, we can compute the required interior volume of the oven by assuming a part envelope volume, consisting of the part size plus spacing on all sides to allow for racking. Assuming a 10 mm margin on all dimensions, the volume envelope require by a single part in cm^3 is:

1 kW: Kiln part envelope = $(17.2 + (1.0 \times 2)) \times (28.4 + (1.0 \times 2)) \times (0.1 + (1.0 \times 2)) = 1226\ cm^3$
5 kW: Kiln part envelope = $(21.8 + (1.0 \times 2)) \times (37.7 + (1.0 \times 2)) \times (0.1 + (1.0 \times 2)) = 1984\ cm^3$

A typical truck kiln that could be used for this operation is the Vesta CEK/TRK 3000 with internal volume of $3.0 \times 10^6\ cm^3$ and input power of 125 kW. The theoretical maximum loading for the kiln is:

1 kW: Maximum Kiln loading = $3.0 \times 10^6\ cm^3 / 1226\ cm^3$/part= 2447 parts
5 kW: Maximum Kiln loading = $3.0 \times 10^6\ cm^3 / 1984\ cm^3$/part= 1513 parts

The number of firing runs is:

1 kW: Number of firing runs = Ceiling(3750 parts/batch / 2447 parts/run) = 2 runs/batch
5 kW: Number of firing runs = Ceiling(9500 parts/batch / 1513 parts/run) = 7 runs/batch

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula developed previously, the load/unload time is:

1 kW: Part handling time = Max((0.3 × ((172 + 284 + 1) / 25.4) - 4.6), 4) = 4.0 sec/part
5 kW: Part handling time = Max((0.3 × ((218 + 377 + 1) / 25.4) - 4.6), 4) = 4.0 sec/part

Now we can compute the total time required to rack a batch of parts per firing run as:

1 kW: Part handling time = 4.0 sec/part × 3750 parts/batch = 15,000 sec/batch = 4.17 hours/batch
5 kW: Part handling time = 4.0 sec/part × 9500 parts/batch = 6052 sec/run = 10.56 hours/batch

Truck handling time is the time required to move a racked batch of parts both to and from the kiln. The time is dependent on plant layout. For costing purposes, we will assume that the kiln is located within 50 feet of the other manufacturing operations, and that the truck can be moved by hand at a speed of 1 foot/second, we estimate the total truck handling time for a batch as:

1 kW: Truck handling time = ((2 × 50 feet/run) / 1 ft/sec.) × 2 runs/batch / 3750 parts/batch = 0.053 sec/part
5 kW: Truck handling time = ((2 × 50 feet/run) / 1 ft/sec.) × 7 runs/batch / 9500 parts/batch = 0.074 sec/part

Total labor cost per part for material handling is:

1 kW: Handling cost per part = ((4.0 + 0.053) sec/part / 3600 sec/hr) × \$45.00/hr / 0.85 = \$0.060/part
5 kW: Handling cost per part = ((4.0 + 0.074) sec/part / 3600 sec/hr) × \$45.00/hr / 0.85 = \$0.060/part

The energy required to heat the oven at the start of a batch run can be calculated using the heat equation: $\Delta Q = \rho v c_p \Delta T$. The ceramic material specific heat is a function of temperature and ranges from 0.45 J/g-K at room temperature to 0.65 J/g-K at 1000°C. Assuming an average part thickness of anode and anode active layer is 265 microns (0.0265 cm), time required to heat a batch of parts from 25-1000°C can be estimated as:

1 kW: Batch part volume = 2447× 488.48 × 0.0265 = 31,675 cm^3
5 kW: Batch part volume = 1513 × 821.86 × 0.0265 = 32,950 cm^3

Using a ceramic material density of 6.1 g/ cm^3, the energy required to heat the SOFC cells is:

1 kW: Heating energy = 6.1 g/cm3 × 31,675 cm^3 × 0.65 J/g-°C × 975°C × 2.8 × 10^{-7} kW-hr/j = 34.28 kW-hr
5 kW: Heating energy = 6.1 g/cm3 × 32,950 cm^3 × 0.65 J/g-°C × 975°C × 2.8 × 10^{-7} kW-hr/j = 35.67 kW-hr

The time required to heat the parts to firing temperature, assuming 90% heating efficiency is:

1 kW: Heating time = 34.28 kW-hr / (125 × 0.9) kW = 0.305 hours
5 kW: Heating time = 35.67 kW-hr / (125 × 0.9) kW = 0.317 hours

The cost per part to heat the kiln is:

1 kW: Heating cost per part = 125 kW × 0.305 hr × \$0.07/kW-hr / 2447 parts = \$0.001/part
5 kW: Heating cost per part = 125 kW × 0.317 hr × \$0.07/kW-hr / 1513 parts = \$0.002/part

Data sheets obtained from industrial furnace manufacturer Yuxiang indicate that the power input required to maintain heat in high temperature furnaces is approximately 50% of the power used to raise the temperature. Thus, the cost per part to maintain the kiln at firing temperature is:

1 kW: Firing cost per part = (125 × 0.5) kW × 3 hours × \$0.07/kW-hr / 2447 parts = \$0.005/part
5 kW: Firing cost per part = (125 × 0.5) kW × 3 hours × \$0.07/kW-hr / 1513 parts = \$0.009/part

Cooling is generally done via natural or forced air convection. Natural convective cooling in the CEK/TRK 3000 is accomplished by opening a set of dampers in the top of the unit, and is generally preferred to minimize cracking caused by thermal gradient stresses that might develop in the ceramic material. Forced air cooling via a blower and plenum system could be used. Blowers for kilns of this size will generally require motors rated at 5 HP (3.73 kW) or less, and costing about \$0.26/hour to run, making the per part cost of cooling negligible. Assuming that total cool-down time is approximately twice the heating time, the machine cost per part for the kiln is:

1 kW: Machine cost per part = (3 + (3 × 0.305)) hours/run × \$25.00/hr / 2447 parts/run / 0.85 = \$0.047/part
5 kW: Machine cost per part = (3 + (3 × 0.317)) hours/run × \$25.00/hr / 1513 parts/run / 0.85 = \$0.076/part

A.6 Final Trim Process

Model Approach

- Laser cut final shape

Process Flow

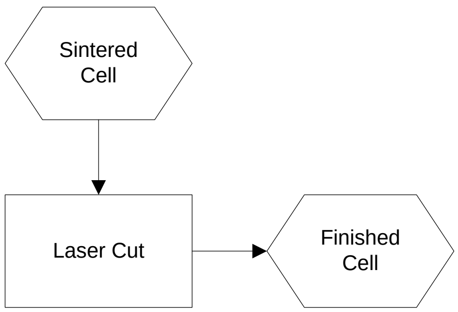
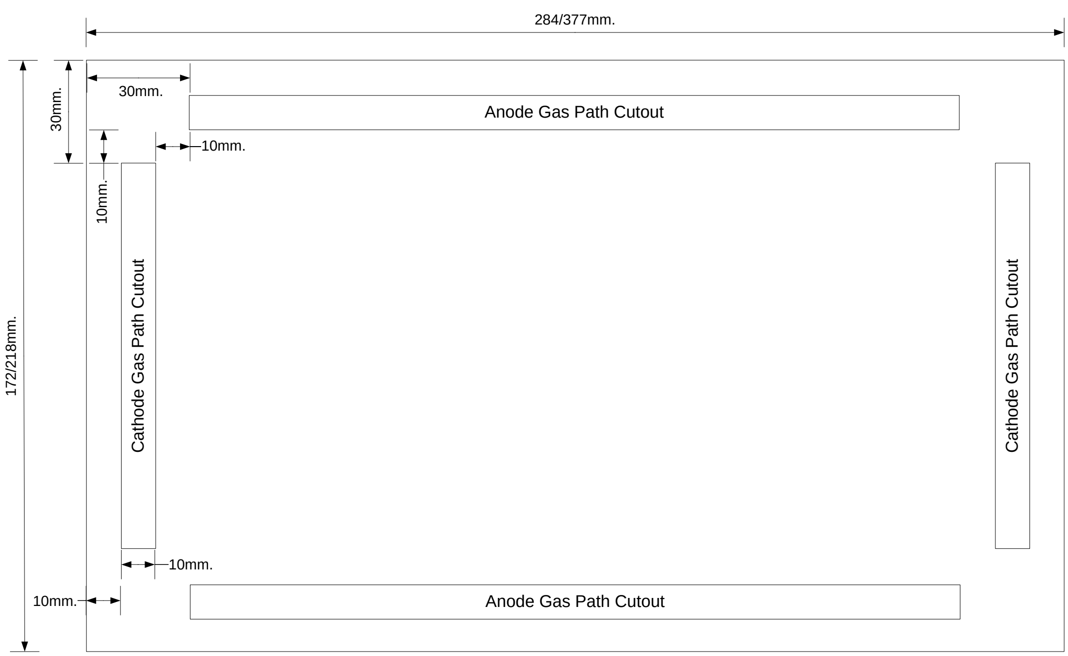


Figure A-6. Final Trim Process

Background

Following sintering, the SOFC cells are laser cut to final dimensions as shown:



Preliminary Analysis

The interconnects for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2
5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

The interconnects will be manufactured from 3 mm thick ferritic stainless steel (SS-441) plate. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 interconnects, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

The 5 kW stack requires 38 interconnects, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Laser Cutting Cost

Assuming a single setup operation requiring 1 operator per batch of parts, the laser etch setup cost per part is:

1 kW: Setup cost per part = 1 hour $\times$ \$45/hour / 3,750 parts / 0.85 = \$0.014/part
5 kW: Setup cost per part = 1 hour $\times$ \$45/hour / 9,500 parts / 0.85 = \$0.006/part

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula developed previously, the total handling time is:

1 kW: Part handling time = Max((0.3 $\times$ ((172 + 284 + 3) / 25.4) - 4.6), 4) = 4.0 sec/part
5 kW: Part handling time = Max((0.3 $\times$ ((218 + 377 + 3) / 25.4) - 4.6), 4) = 4.0 sec/part

The total cutting length for the cell is:

1 kW: Cutting length = (2 $\times$ (172 + 284)) + (4 $\times$ (112 + 10)) + (4 $\times$ (224 + 10)) = 2336 mm
5 kW: Cutting length = (2 $\times$ (218 + 377)) + (4 $\times$ (158 + 10)) + (4 $\times$ (317 + 10)) = 3170 mm

Linde suggests that laser cutting of 1 mm thick stainless steel be performed using a 1,500 W YAG laser under pure nitrogen flow of 8.0 m^3/hr at a maximum speed of 7.0 m/min (0.117 m/sec). Assuming that the sintered ceramic has similar properties, the time to cut the cells is:

1 kW: Cutting time = 2.336 m / 0.117 m/sec = 19.97sec/part
5 kW: Cutting time = 3.170 m / 0.117 m/sec = 27.09 sec/part

Using a 1.5 kW laser, the energy cost per part is:

1 kW: Etching energy cost = 1.5 kW × $0.07/kW-hr × 19.97 sec/part / 3600 sec/hr < $0.001/part

5 kW: Etching energy cost = 1.5 kW × $0.07/kW-hr × 27.09 sec/part / 3600 sec/hr < $0.001/part

Atlas Copco, in an article for Pharmaceutical Processing, provides a cost of on-site generated nitrogen of about $0.21/100ft^3 ($0.074/m^3). At a consumption rate of 8.0 m^3/hr, the nitrogen material cost is:

1 kW: Etching material cost = 8.0 m^3/hr × $0.074/m^3 × 19.97 sec/part / 3600 sec/hr = $0.003/part

5 kW: Etching material cost = 8.0 m^3/hr × $0.074/m^3 × 27.09 sec/part / 3600 sec/hr = $0.004/part

With cycle times of less than 0.5 minutes per part, we will assume that 1 operator can cover 1 cutting station, making the total labor cost:

1 kW: Etching labor cost = 1 × ((4.0 + 19.97) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.353/part

5 kW: Etching labor cost = 1 × ((4.0 + 27.09) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.457/part

Total machine cost per part is:

1 kW: Etching machine cost = ((4.0 + 19.97) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $0.196/part

5 kW: Etching machine cost = ((4.0 + 27.09) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $0.254/part

A.7 Interconnect Manufacturing Process

Model Approach

- Ferritic stainless steel stamping operation
- Laser etching operation
- Perovskite coating operation
- Heat treating operation

Process Flow

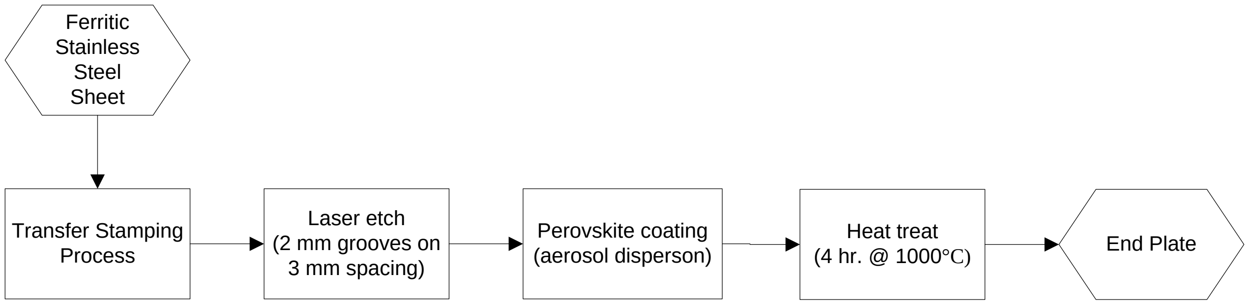
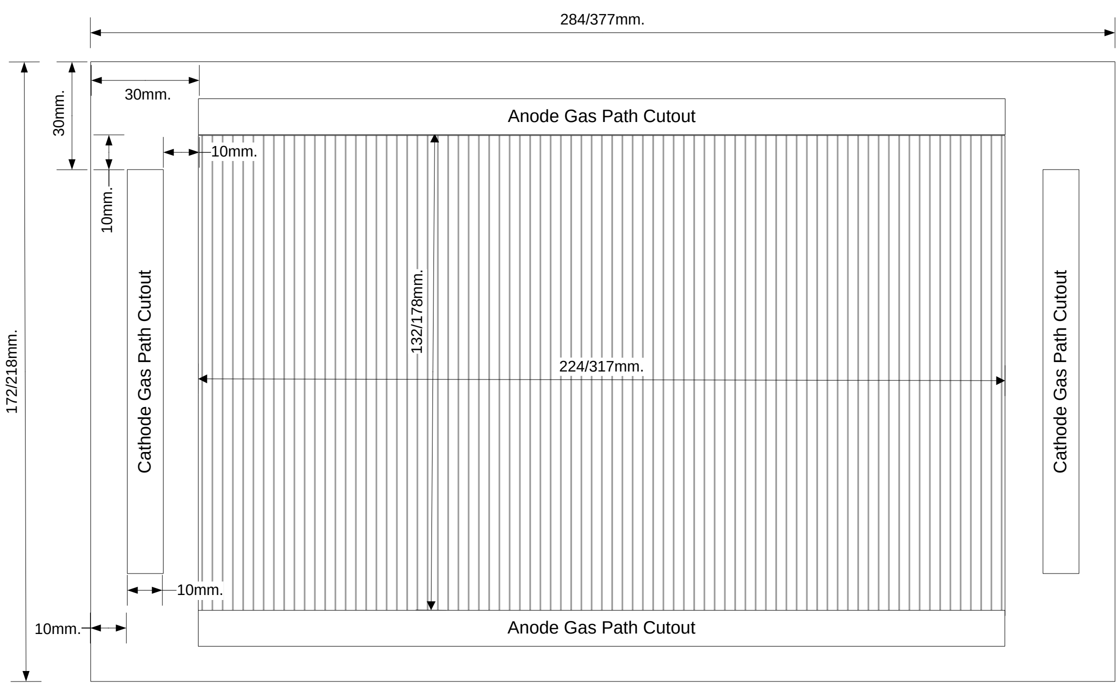


Figure A-7. Interconnect Manufacturing Process

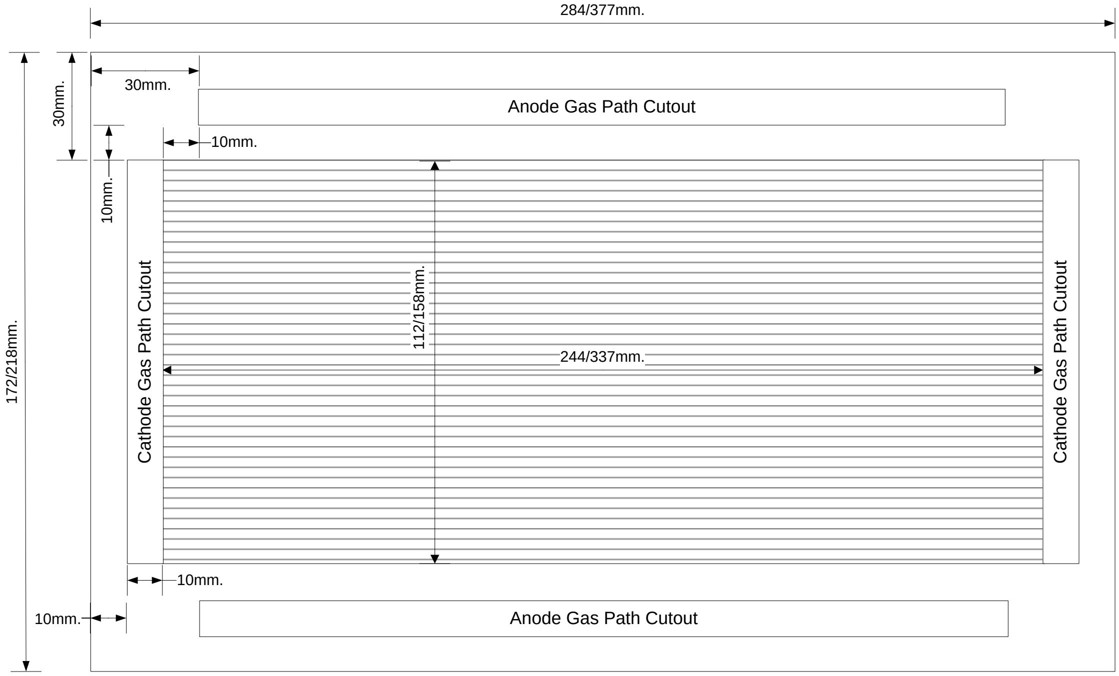
Background

The interconnect plates are designed for anode and cathode gas cross flow by etching the two sides of the stamped plates as shown:

Anode Side



Cathode Side



Preliminary Analysis

The interconnects for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2

5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

The interconnects will be manufactured from 3 mm thick ferritic stainless steel (SS-441) plate. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 interconnects, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

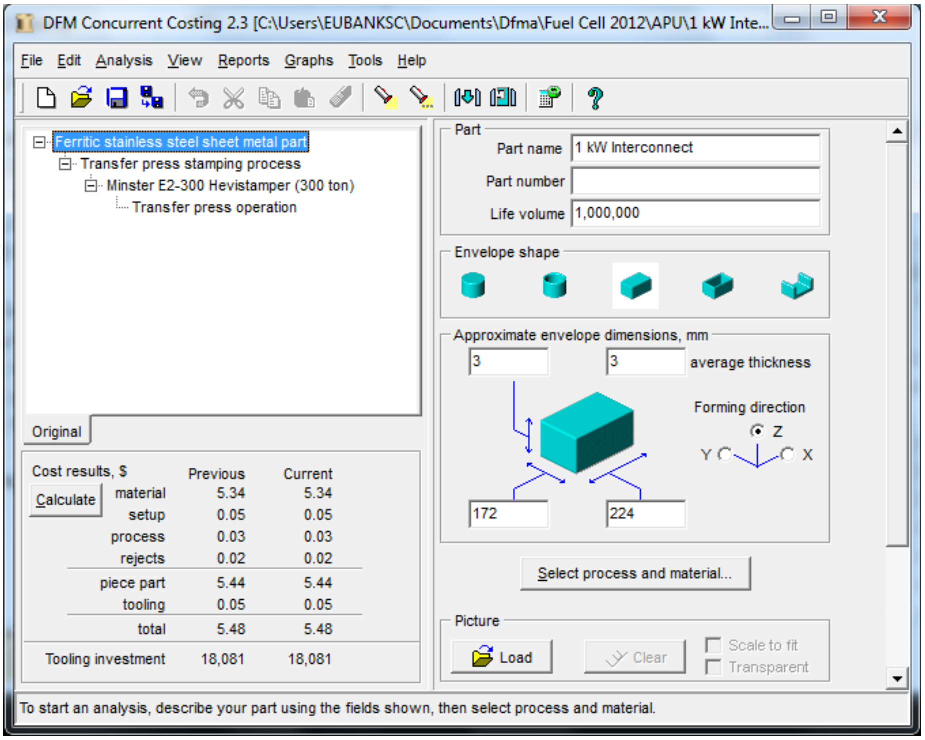
The 5 kW stack requires 38 interconnects, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

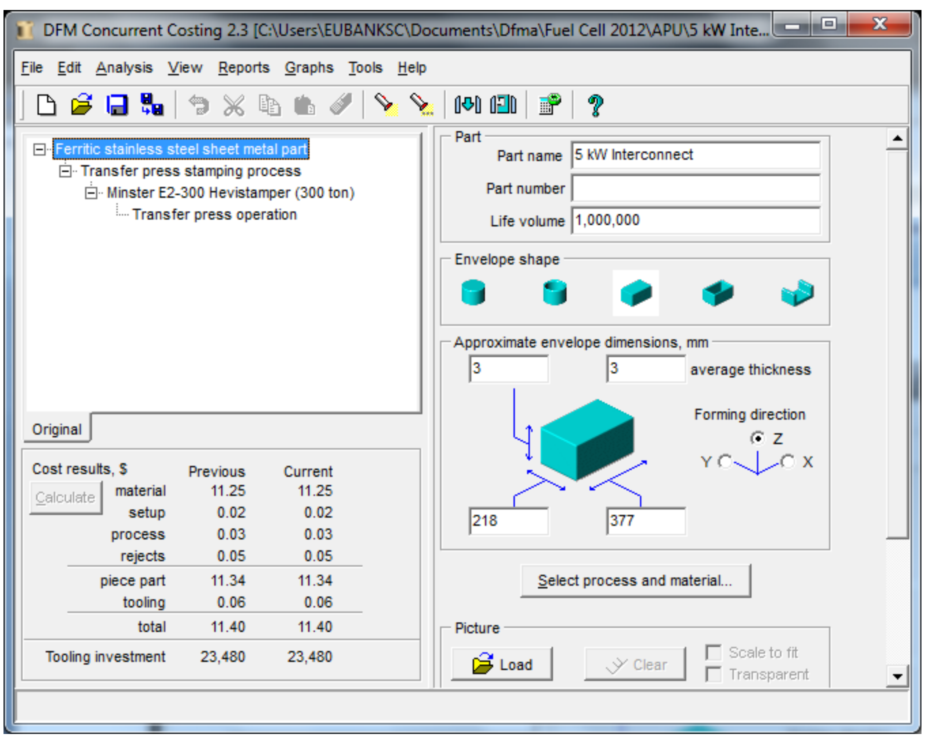
Transfer Stamping Processing Cost

The BDI software provides pre-programmed cost models for the transfer stamping operations used to manufacture the interconnect plate blanks. The resulting analysis is shown in the following screen shots:

1 kW Interconnects



5 kW Interconnects



Summarizing the BDI per part cost output:

	1 kW	5 kW
Material	\$6.62	\$11.25
Setup	\$0.05	\$0.02
Machine	\$0.03	\$0.03
Scrap	\$0.02	\$0.05
Tooling	\$0.05	\$0.06
Total	\$6.77	\$11.40

Laser Etching Processing Cost

Assuming a single setup operation requiring 1 operator per batch of parts, the laser etch setup cost per part is:

1 kW: Setup cost per part = 1 hour $\times$ \$45/hour / 3,750 parts / 0.85 = \$0.014/part
5 kW: Setup cost per part = 1 hour $\times$ \$45/hour / 9,500 parts / 0.85 = \$0.006/part

Part load/unload, which may be manual or robotic, will be driven by overall part size. Because the part will be turned in order to etch both sides, additional time equal to half of the load/unload time will be added. Using the handling time formula developed previously, the total handling time is:

1 kW: Part handling time = 1.5 $\times$ Max((0.3 $\times$ ((172 + 284 + 3) / 25.4) - 4.6), 4) = 6.0 sec/part
5 kW: Part handling time = 1.5 $\times$ Max((0.3 $\times$ ((218 + 377 + 3) / 25.4) - 4.6), 4) = 6.0 sec/part

In "Optimization of Solid Oxide Fuel Cell Interconnect Design," Pulagam found that a 60% interconnect contact produced the best combination of electrical and thermal performance using a 2 mm wide by 1 mm deep flow channel. This provides an overall channel + rib spacing of 5 mm. Each plate will be etched in along its length on the anode side, and along its width on the cathode side. The number of full length channels on each side is:

Number of anode channels = Floor(Anode etching width (mm) / 5 mm)
Number of cathode channels = Floor(Cathode etching width (mm) / 5 mm)

1 kW: Number of anode channels = Floor(224/5) = 44
1 kW: Number of cathode channels = Floor(112/5) = 22

5 kW: Number of anode channels = Floor(317/5) = 63

5 kW: Number of cathode channels = Floor(158/5) = 31

The total etched length for each side is:

Anode side etched length = Number of anode channels × Etched length (mm)
Cathode side etched length = Number of cathode channels × Etched length (mm)

1 kW: Anode side etched length = 44 × 132 = 5,808 mm = 5.81 m
1 kW: Cathode side etched length = 22 × 244 = 5,368 = 5.37 m

5 kW: Anode side etched length = 63 × 178 = 11,214 mm = 11.21 m
5 kW: Cathode side etched length = 31 × 337 = 10,447 mm = 10.45 m

While information on deep laser etching is difficult to find, Linde suggests that laser cutting of 1 mm thick stainless steel be performed using a 1,500 W YAG laser under pure nitrogen flow of 8.0 m^3/hr at a maximum speed of 7.0 m/min (0.117 m/sec). Total time to etch the plates is:

1 kW: Part etching time = (5.81 + 5.37) m / 0.117 m/sec = 95.56 sec/part
5 kW: Part etching time = (11.21 + 10.45) m / 0.117 m/sec = 185.13 sec/part

Using a 1.5 kW laser, the energy cost per part is:

1 kW: Etching energy cost = 1.5 kW × $0.07/kW-hr × 95.56 sec/part / 3600 sec/hr = $0.003/part
5 kW: Etching energy cost = 1.5 kW × $0.07/kW-hr × 185.13sec/part / 3600 sec/hr = $0.005/part

Atlas Copco, in an article for Pharmaceutical Processing, provides a cost of on-site generated nitrogen of about $0.21/100ft^3 ($0.074/m^3). At a consumption rate of 8.0 m^3/hr, the nitrogen material cost is:

1 kW: Etching material cost = 8.0 m^3/hr × $0.074/m^3 × 95.56 sec/part / 3600 sec/hr = $0.016/part
5 kW: Etching material cost = 8.0 m^3/hr × $0.074/m^3 × 185.13sec/part / 3600 sec/hr = $0.030/part

With cycle times of 1.5 to 3 minutes per part, we will assume that 1 operator can cover 3 etching stations, making the total labor cost:

1 kW: Etching labor cost = 0.33 × ((6.0 + 95.56) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.493/part
5 kW: Etching labor cost = 0.33 × ((6.0 + 185.13) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.928/part

Total machine cost per part is:

1 kW: Etching machine cost = ((6.0 + 95.56) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $0.830/part
5 kW: Etching machine cost = ((6.0 + 185.13) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $1.562/part

Aerosol Coating Processing Cost

Assuming a single setup operation requiring 1 operator per batch of parts, the spray deposition setup cost per part is:

1 kW: Setup cost per part = 1 hour $\times$ $45/hour / 3,750 parts / 0.85 = $0.014/part
5 kW: Setup cost per part = 1 hour $\times$ $45/hour / 9,500 parts / 0.85 = $0.006/part

Part load/unload, which may be manual or robotic, will be driven by overall part size. Because the part will be turned in order to coat both sides, additional time equal to half of the load/unload time will be added. Using the handling time formula developed previously, the total handling time is:

1 kW: Part handling time = 1.5 $\times$ Max((0.3 $\times$ ((172 + 284 + 3) / 25.4) - 4.6), 4) = 6.0 sec/part
5 kW: Part handling time = 1.5 $\times$ Max((0.3 $\times$ ((218 + 377 + 3) / 25.4) - 4.6), 4) = 6.0 sec/part

The perovskite coating is deposited via aerosol spray to a depth of 3 microns (0.003 mm). The perovskite material cost is estimated at $150.00/kg ($0.15/g), and has a material density of approximately 6.1 g/cm^3. The material cost per cm^3 of part area is:

Material cost = 6.1 g/cm^3 $\times$ $0.15/g = $0.915/cm^3

Assuming a 90% spray efficiency, and allowing for 25 mm over spray on the 4 edges, the total deposited material per coated side is:

1 kW: Deposited material = 2 $\times$ (17.2 + 5) cm $\times$ (28.4 + 5) cm $\times$ 0.0003 cm = 0.445 cm^3
5 kW: Deposited material = 2 $\times$ (21.8 + 5) cm $\times$ (37.7 + 5) cm $\times$ 0.0003 cm = 0.687 cm^3

Total coating material cost is:

1 kW: Coating material cost = 0.445 cm^3 $\times$ $0.915/cm^3 < $0.407
5 kW: Coating material cost = 0.687 cm^3 $\times$ $0.915/cm^3 < $0.629

Deposited depth is a function of flow rate, spray width and nozzle speed:

Coating depth = Flow rate (mm^3/sec) / (Spray width (mm) $\times$ Nozzle speed (mm/sec))

Spray nozzle manufacturers will generally specify a maximum flow rate associated with a particular nozzle. Therefore, given a flow rate, coated width and coating depth, the nozzle speed is calculated as:

Nozzle speed (mm/sec) = Flow rate (mm^3/sec) / (Spray width (mm) × Coating depth (mm))

Using the SonoTek Flexicoat Impact nozzle system as an example, the maximum precision spray width is approximately 50 mm and maximum nozzle speed of 400 mm/sec. Assuming a maximum coating flow rate of 333 mm^3/sec (20 ml/min), the nozzle speed is:

Nozzle speed = Min(333 / (50 × 0.003), 400) = 400 mm/sec

The time to coat both sides of the interconnect plate, and allowing for 25 mm over spray on the 4 edges is:

1 kW: Coating time per part = 2 × ((172 + 50) mm × (284 + 50) mm / (50 mm × 400 mm/sec)) = 7.41 sec/part
5 kW: Coating time per part = 2 × ((218 + 50) mm × (377 + 50) mm / (50 mm × 400 mm/sec)) = 11.44 sec/part

Assuming 1 operator per spray station, the total labor cost is:

1 kW: Coating labor cost = ((6.0 + 7.41) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.197/part
5 kW: Coating labor cost = ((6.0 + 11.44) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.256/part

Total machine cost per part is:

1 kW: Coating machine cost = ((6.0 + 7.41) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $0.110/part
5 kW: Coating machine cost = ((6.0 + 11.44) sec/part / 3600 sec/hr) * $25.00/hr / 0.85 = $0.142/part

Heat Treating Processing Cost

The interconnect coating process call for heat treatment at 1000°C (1472°F) for 4 hours after the part reaches temperature. For a batch type furnace, assume a single setup operation requiring 1 operator per batch of parts. The setup cost per part is:

1 kW: Setup cost per part = 1 hour × $45/hour / 3,750 parts / 0.85 = $0.014/part
5 kW: Setup cost per part = 1 hour × $45/hour / 9,500 parts / 0.85 = $0.006/part

Assuming a batch type industrial furnace, we can compute the required interior volume of the furnace by assuming a part envelope volume, consisting of the part size plus spacing on all sides to allow for racking. Assuming a 10 mm margin on all dimensions, the volume envelope require by a single part in cm^3 is:

1 kW: Furnace part envelope = $(17.2 + (1.0 \times 2)) \times (28.4 + (1.0 \times 2)) \times (0.3 + (1.0 \times 2))$ = 1342.5 cm^3
5 kW: Furnace part envelope = $(21.8 + (1.0 \times 2)) \times (37.7 + (1.0 \times 2)) \times (0.3 + (1.0 \times 2))$ = 2173 cm^3

A typical furnace that could be used for this operation is the Lucifer EL5-483636 with internal volume of 1.78×10^6 cm^3 and input power of 126 kW. The theoretical maximum loading for the furnace is:

1 kW: Maximum Furnace loading = 1.78×10^6 cm^3 / 1342.5 cm^3/part= 1326 parts/run
5 kW: Maximum Furnace loading = 1.78×10^6 cm^3 / 2173 cm^3/part= 819 parts/run

The number of firing runs is:

1 kW: Number of firing runs = Ceiling(3750 parts/batch / 1326 parts/run) = 3 runs/batch
5 kW: Number of firing runs = Ceiling(9500 parts/batch / 819 parts/run) = 12 runs/batch

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula developed previously, the load/unload time is:

1 kW: Part handling time = Max((0.3 $\times$ ((172 + 284 + 1) / 25.4) - 4.6), 4) = 4.0 sec/part
5 kW: Part handling time = Max((0.3 $\times$ ((218 + 377 + 1) / 25.4) - 4.6), 4) = 4.0 sec/part

Now we can compute the total time required to rack a batch of parts per firing run as:

1 kW: Part handling time = 4.0 sec/part $\times$ 3750 parts/batch = 15,000 sec/batch = 4.17 hours/batch
5 kW: Part handling time = 4.0 sec/part $\times$ 9500 parts/batch = 6052 sec/batch = 10.56 hours/batch

Truck handling time is the time required to move a racked batch of parts both to and from the furnace. The time is dependent on plant layout. For costing purposes, we will assume that the furnace is located within 50 feet of the other manufacturing operations, and that the truck can be moved by hand at a speed of 1 foot/second, we estimate the total truck handling time for a batch as:

1 kW: Truck handling time = ((2 $\times$ 50 feet/run) / 1 ft/sec.) $\times$ 3 runs/batch / 3750 parts/batch = 0.080 sec/part
5 kW: Truck handling time = ((2 $\times$ 50 feet/run) / 1 ft/sec.) $\times$ 12 runs/batch / 9500 parts/batch = 0.126 sec/part

Total labor cost per part for material handling is:

1 kW: Handling cost per part = ((4.0 + 0.080) sec/part / 3600 sec/hr) $\times$ \$45.00/hr / 0.85 = \$0.060/part
5 kW: Handling cost per part = ((4.0 + 0.126) sec/part / 3600 sec/hr) $\times$ \$45.00/hr / 0.85 = \$0.061/part

The energy required to heat the furnace at the start of a batch run can be calculated using the heat equation: $\Delta Q=\rho v c_p \Delta T$. The specific heat for (SS-441) is 0.5 J/g-K. The coating is only 2-3 microns, and its contribution to part volume or overall heat capacity is negligible. The time required to heat a batch of parts from 25-1000°C can be estimated as:

1 kW: Run part volume = 1326 $\times$ 488.48 $\times$ 0.3 = 194,444 cm^3
5 kW: Run part volume = 819 $\times$ 821.86 $\times$ 0.3 = 201,931 cm^3

Using a material density of 8.0 g/ cm^3, the energy required to heat the SOFC cells is:

1 kW: Heating energy = 8.0 g/cm^3 $\times$ 194,444 cm^3 $\times$ 0.5 J/g-°C $\times$ 975°C $\times$ 2.8 $\times$ 10^{-7} kW-hr/j = 212 kW-hr
5 kW: Heating energy = 8.0 g/cm^3 $\times$ 201,931 cm^3 $\times$ 0.5 J/g-°C $\times$ 975°C $\times$ 2.8 $\times$ 10^{-7} kW-hr/j = 221 kW-hr

In their report "Understanding Power Losses in Vacuum Furnaces," Solar states that the power required to heat the furnace hot zone components of a furnace of similar size to 2000°F (1093°C) is approximately 97 kW-hr. The total energy required to heat the furnace is:

1 kW: Heating energy = 97 + 212 = 309 kW-hr
5 kW: Heating energy = 97 + 221 = 318 kW-hr

Power losses during the dwell time at 1000°C are estimated to be 100 kW/hr. At a heating rate of 11°C/min, the furnace requires 88.6 minutes (1.48 hours) to reach the heat treat temperature. The total cost per part to heat the furnace is:

1 kW: Heating cost per part = 309 kW-hr $\times$ \$0.07/kW-hr / 1326 parts = \$0.016/part
5 kW: Heating cost per part = 318 kW-hr $\times$ \$0.07/kW-hr / 819 parts = \$0.027/part

At a loss of 100 kW/hr, the cost per part to maintain the furnace at treatment temperature is:

1 kW: Firing cost per part = 100 kW $\times$ 4 hours $\times$ \$0.07/kW-hr / 1326 parts = \$0.022/part
5 kW: Firing cost per part = 100 kW $\times$ 4 hours $\times$ \$0.07/kW-hr / 819 parts = \$0.034/part

Cooling is accomplished by removing the parts from the oven and allowing to air cool. Total energy cost for the heat treating process is:

1 kW: Energy cost per part = \$0.016 + \$0.022 = \$0.038/part
5 kW: Energy cost per part = \$0.027 + \$0.034 = \$0.061/part

The machine cost per part is:

1 kW: Heat treat machine cost = (1.48 + 4) hours/run × \$25.00/hr / 1326 parts/run / 0.85 = \$0.121/part

5 kW: Heat treat machine cost = (1.48 + 4) hours/run × \$25.00/hr / 819 parts/run / 0.85 = \$0.196/part

A.8 Picture Frame Production Process

Model Approach

- Ferritic stainless steel stamping operation

Process Flow

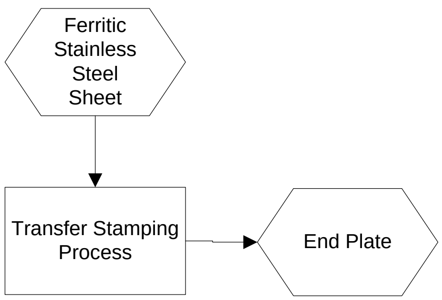
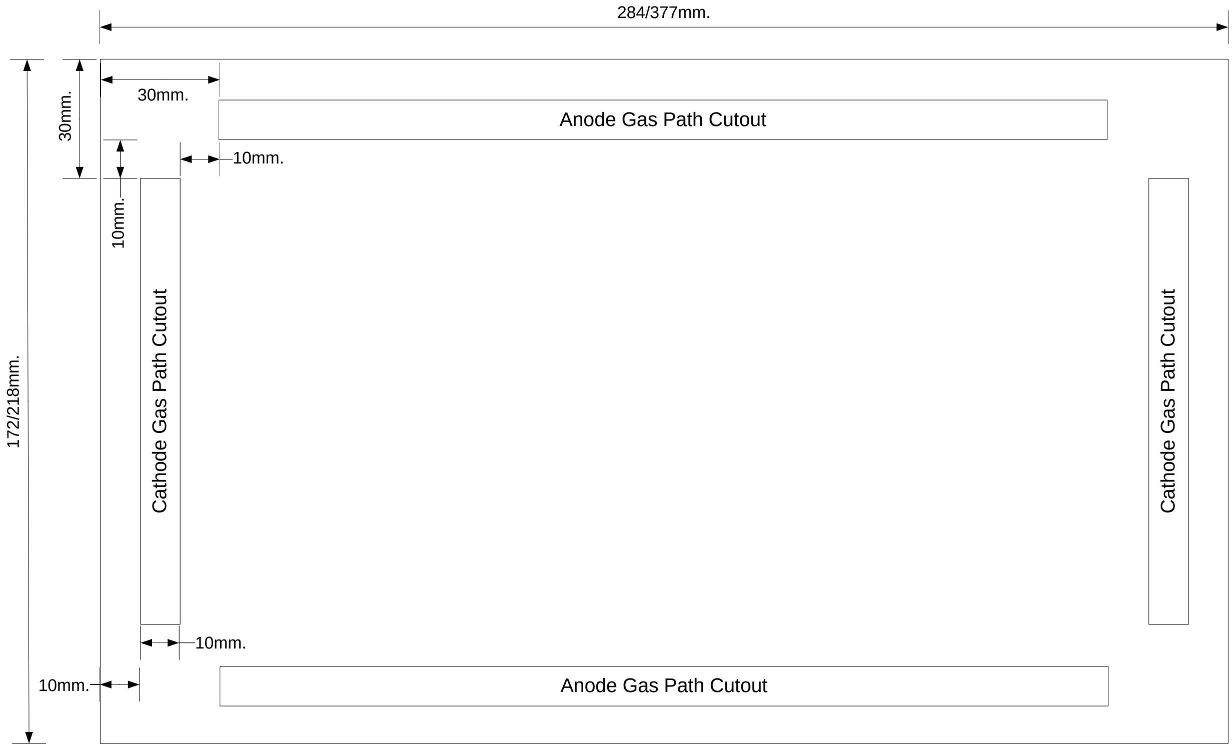


Figure A-8. Picture Frame Production Process

Background

The picture frames are designed as spacers between the cathode side of the interconnect plate and anode support as shown:



Preliminary Analysis

The interconnects for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2

5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

The interconnects will be manufactured from 3 mm thick ferritic stainless steel (SS-441) plate. Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 interconnects, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

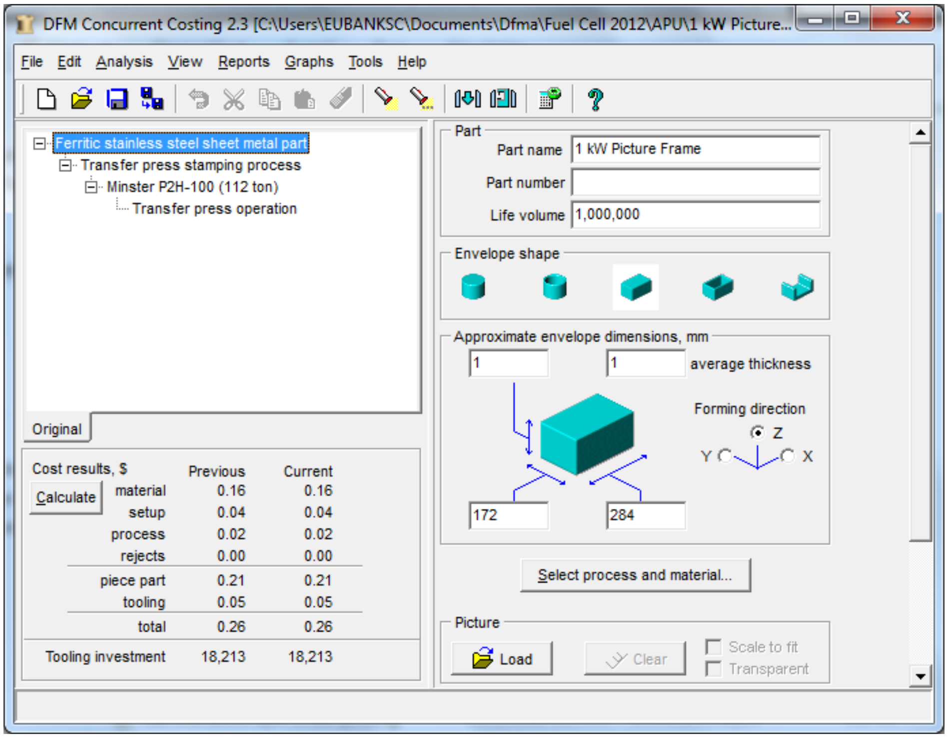
The 5 kW stack requires 38 interconnects, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

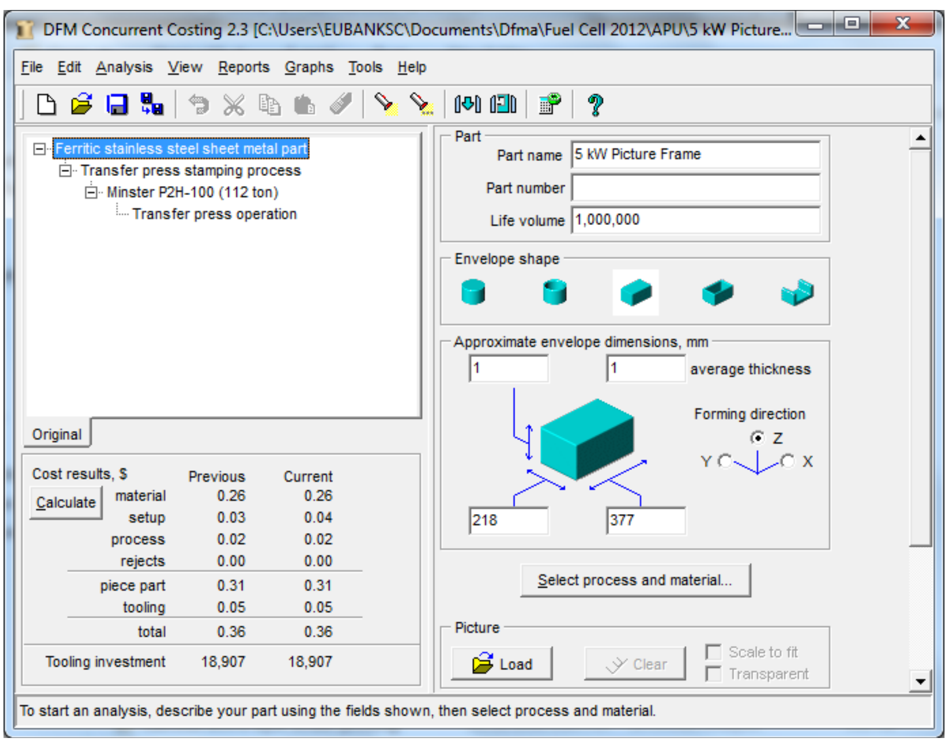
Transfer Stamping Processing Cost

The BDI software provides pre-programmed cost models for the transfer stamping operations used to manufacture the picture frames. The resulting analysis is shown in the following screen shots:

1 kW Picture Frames



5 kW Picture Frames



Summarizing the BDI per part cost output:

	1 kW	5 kW
Material	$0.16	$0.26
Setup	$0.04	$0.04
Machine	$0.02	$0.02
Scrap	$0.00	$0.00
Tooling	$0.05	$0.05
Total	$0.26	$0.36

A.9 Glass-Ceramic Sealing Process

Model Approach

- Calculate glass-ceramic sealant batch size
- Calculate glass-ceramic sealant production cost
- Calculate glass-ceramic sealant application cost

Process Flow

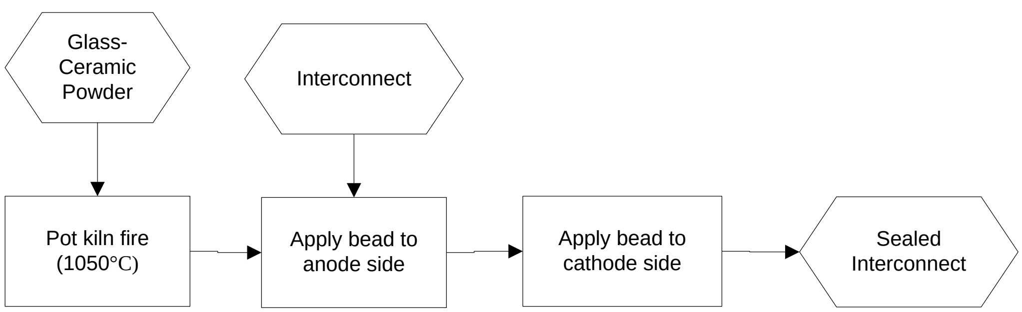
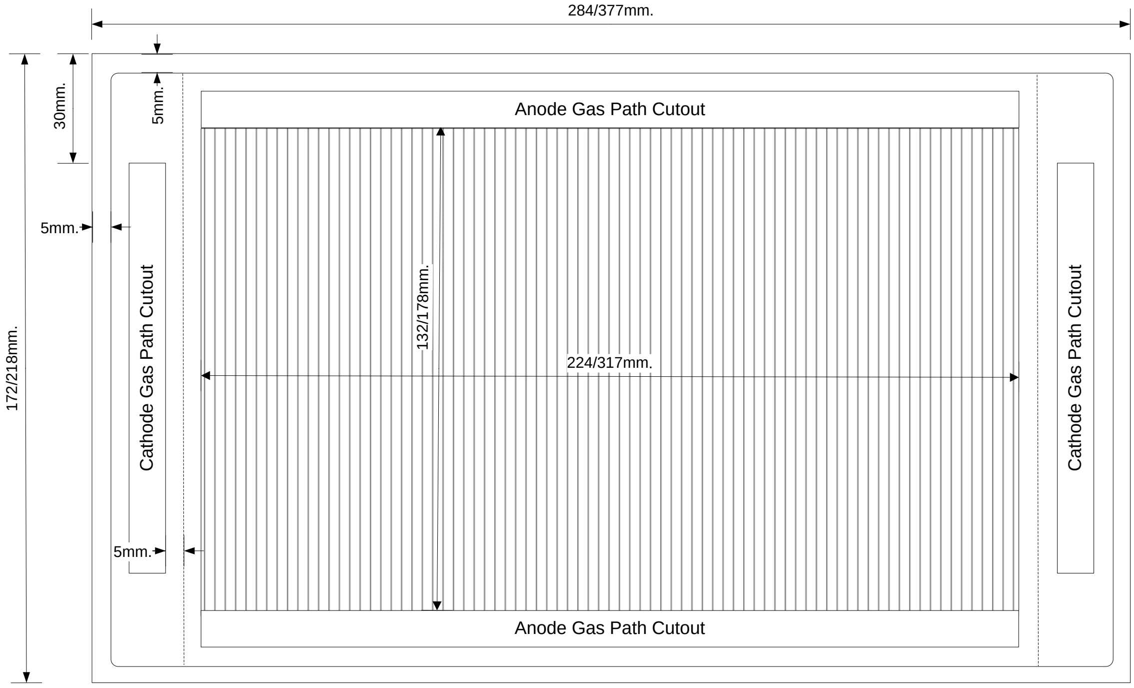


Figure A-9. Glass-Ceramic Sealing Process

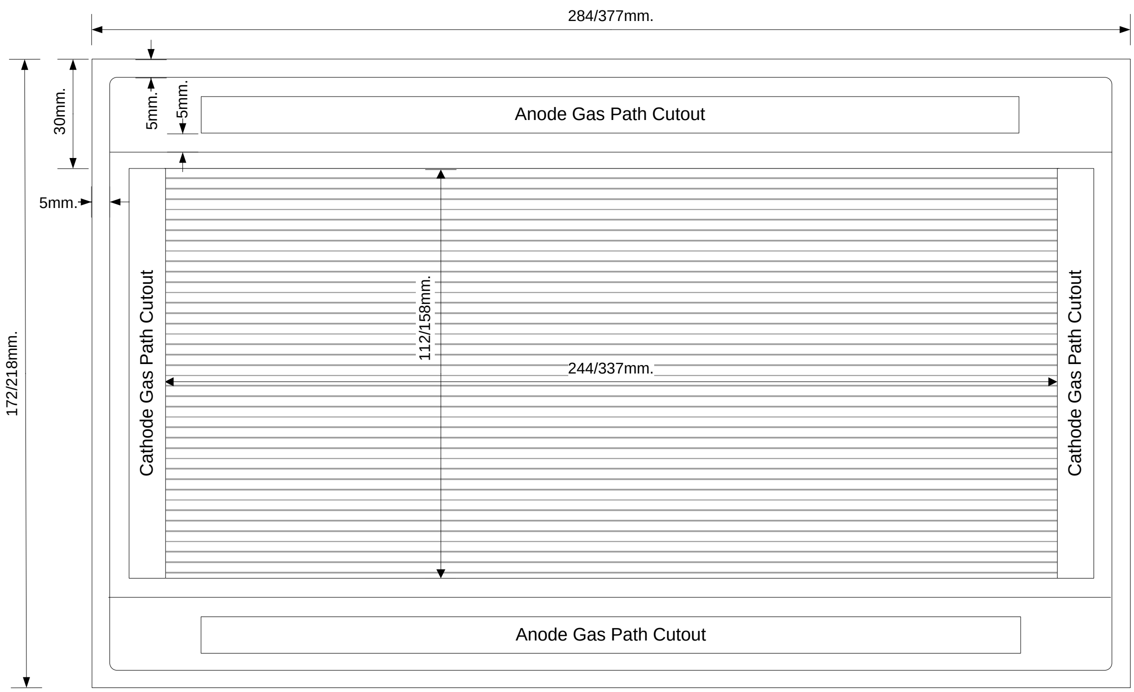
Background

The sealant bead (dashed lines) is applied to the two sides of the interconnect plates as shown:

Anode Side



Cathode Side



Preliminary Analysis

The interconnects for this analysis will be working in two systems for which the part size is:

1 kW Stack: 172 mm width $\times$ 284 mm length = 488.48 cm^2

5 kW Stack: 218 mm width $\times$ 377 mm length = 821.86 cm^2

Batch sizes will be calculated based on a quarterly production schedule producing 1,000 stacks per year. The 1 kW stack requires 15 interconnects, requiring quarterly production of:

1 kW: Quarterly production = 15 parts/stack $\times$ 250 stacks = 3,750 parts

The 5 kW stack requires 38 interconnects, requiring quarterly production of:

5 kW: Quarterly production = 38 parts/stack $\times$ 250 stacks = 9,500 parts

Sealant Batch Size

The sealant will be applied to areas that are 10 mm wide, and needs to fill a gap of about 2 microns (nearly flush) on both sides of the interconnect plates and one side of the picture frame with the same seal length as the cathode side. Assuming a maximum finished seal width of 8 mm, the total seal cross-sectional area is

Seal cross sectional area = 8 mm wide $\times$ 0.006 mm high = 0.048 mm^2

Assuming application in a round bead, the required bead diameter that will yield the same cross sectional area is:

Seal dispense diameter = $2 \times (0.048/\pi)^{1/2} = 0.247$ mm

The total seal length per side based on the above drawing is:

1 kW: Anode Seal Length: $(2 \times 274) + (4 \times 162) = 1196$ mm
1 kW: Cathode Seal Length: $(4 \times 274) + (2 \times 162) = 1420$ mm

5 kW: Anode Seal Length: $(2 \times 367) + (4 \times 208) = 1566$ mm
5 kW: Cathode Seal Length: $(4 \times 367) + (2 \times 208) = 1884$ mm

The total volume of seal material required per part is:

1 kW: $0.048 \times (1196 + (2 \times 1420)) = 996\ mm^3 = 0.194\ cm^3$
5 kW: $0.048 \times (1566 + (2 \times 1884)) = 1317\ mm^3 = 0.256\ cm^3$

The total sealant batch size (cm^3) for a batch of interconnect plates and picture frames is:

1 kW: 0.194 cm^3/cell $\times$ 3750 cells = 727.5cm^3
5 kW: 0.256 cm^3/cell $\times$ 9500 cells = 2432 cm^3

A typical sealant is the Ceredyne VIOX V1649 glass ceramic sealant, consisting of 50/50 borosilicate glass/lanthanum oxide. Ceredyne lists the sealant density as 4 g/cm^3, giving the sealant weight per cell and per batch as:

Sealant weight per cell:
1 kW: 4 $g/cm^3 \times 0.194\ cm^3/cell = 0.776\ g/cell$
5 kW: 4 $g/cm^3 \times 0.256\ cm^3/cell = 1.024\ g/cell$

Sealant batch size (kg):
1 kW: 0.776 g/cell × 3750 cells = 2.910 kg
5 kW: 1.024 g/cell × 9500 cells = 9.728 kg

Sealant Production Cost

Setup cost

Assuming a single setup operation requiring 1 operator per batch of parts, the setup cost per part is:

1 kW: Setup cost per part = 1 hour × \$45/hour / 3,750 parts / 0.85 = \$0.014/part
5 kW: Setup cost per part = 1 hour × \$45/hour / 9,500 parts / 0.85 = \$0.006/part

Material cost

Internet searches yielded a consensus material cost for lanthanum oxide of \$15/kg, and borosilicate glass of \$2/kg, giving a 50/50 mixture cost of \$8.50/kg. The material cost per part is:

1 kW: \$8.50/kg × 6.70 g/cell / 1000 g/kg = \$0.057/part
5 kW: \$8.50/kg × 8.83 g/cell / 1000 g/kg = \$0.075/part

Sealant Application Cost

Assuming a single setup operation requiring 1 operator per batch of parts, the sealant application station setup cost per part is:

1 kW: Setup cost per part = 1 hour × \$45/hour / 3,750 parts / 0.85 = \$0.014/part
5 kW: Setup cost per part = 1 hour × \$45/hour / 9,500 parts / 0.85 = \$0.006/part

Part load/unload, which may be manual or robotic, will be driven by overall part size. Because the sealant will be applied to 3 total sides, additional time equal to half of the load/unload time will be added. Using the handling time formula developed previously, the total handling time is:

1 kW: Part handling time = 1.5 × Max((0.3 × ((172 + 284 + 1) / 25.4) - 4.6), 4) = 6.0 sec/part

5 kW: Part handling time = 1.5 × Max((0.3 × ((218 + 377 + 1) / 25.4) - 4.6), 4) = 6.0 sec/part

The Boothroyd-Dewhurst DFMA™ software tool estimate for the bead application rate of viscous sealants is 2 in/sec (51 mm/sec) with an applicator positioning time of 0.4 seconds. Assuming that the bead is applied to the part perimeter in a single bead, followed by the two beads between the unused gas path and flow field, there will be 4 total re-positionings: move applicator to start of perimeter bead, move applicator to start of first gas path bead, move applicator to second gas path bead, move applicator to home position. The total application

1 kW: Sealant application time = (4 × 0.4) + ((1196 + (2 × 1420)) mm / 51 mm/sec) = 80.74 sec/part
5 kW: Sealant application time = (4 × 0.4) + ((1566 + (2 × 1884)) mm / 51 mm/sec) = 106.19 sec/part

At total processing time of around 1.5 minute per part, we will assume that 1 operator can cover 2 sealing stations, making the total labor cost:

1 kW: Sealant application labor cost = 0.5 × ((6.0 + 80.74) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.637/part
5 kW: Sealant application labor cost = 0.5 × ((6.0 + 106.19) sec/part / 3600 sec/hr) * $45.00/hr / 0.85 = $0.825/part

The machine cost per part is:

1 kW: Sealant application machine cost = ((6.0 + 80.74) sec/part / 3600 sec/hr) × $25.00/hr / 0.85 = $0.709/part
5 kW: Sealant application machine cost = ((6.0 + 106.19) sec/part / 3600 sec/hr) × $25.00/hr / 0.85 = $0.917/part

A.10 Stack Brazing Process

Model Approach

- Stack Brazing
    - Part handling time labor cost based on part size per BDI formula and throughput; 4 second minimum
    - Process cost based on oven energy cost plus standard machine rate

Process Flow

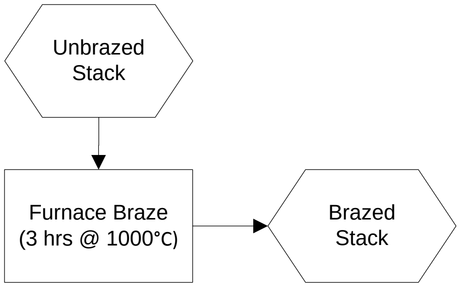


Figure A-10. Stack Brazing Process

Preliminary Analysis

The stacks for this analysis will be working in two systems. The overall part envelope is bounded by the end plate length and width and the stack height. The stack height is estimated based on a thickness of about 3.5 mm per repeat cell, plus 15 mm each for the two end plates. The total stack envelope estimated as:

1 kW Stack: 232 mm width × 344 mm length × ((3.5*15) + 30) mm high = 6,584 cm^3
5 kW Stack: 278 mm width × 437 mm length × ((3.5*38) + 30) mm high = 24,922 cm^3

Batch sizes will be calculated based on a quarterly production of 250 stacks schedule producing 1,000 stacks per year.

Stack brazing cost

We will assume a furnace brazing cycle of 800°C (1832°F) for 3 hours. For a batch type oven, assume a single setup operation requiring 1 operator per batch of parts. The setup cost per part is:

Setup cost per part = 1 hour × $45/hour / 250 parts / 0.85 = $0.212/part

Assuming a batch type industrial furnace, we can compute the required interior volume of the oven by assuming a part envelope volume, consisting of the part size plus spacing on all sides to allow for racking. Assuming a 20 mm margin on all dimensions, the volume envelope require by a single part in cm^3 is:

1 kW: Furnace part envelope = (23.2 + 2) × (34.4 + 2) × (8.25 + 2) = 9,402 cm^3
5 kW: Furnace part envelope = (27.8 + 2) × (43.7 + 2) × (16.3 + 2) = 24,922 cm^3

A typical furnace that could be used for this operation is the Grieve HD-484848 with internal volume of 64 ft^3 (1.8×10^6 cm^3) and input power of 92 kW. The theoretical maximum loading for the furnace is:

1 kW: Maximum Furnace loading $= 1.8 \times 10^6$ cm^3 / 9,402 cm^3/part= 192 parts
5 kW: Maximum Furnace loading $= 1.8 \times 10^6$ cm^3 / 24,922 cm^3/part= 73 parts

The number of firing runs is:

1 kW: Number of firing runs = Ceiling(250 parts/batch / 192 parts/run) = 2 runs/batch
5 kW: Number of firing runs = Ceiling(250 parts/batch / 73 parts/run) = 4 runs/batch

Part load/unload, which may be manual or robotic, will be driven by overall part size. Using the handling time formula developed previously, the load/unload time is:

1 kW: Part handling time = Max((0.3 × ((232 + 344 + 82.5) / 25.4) - 4.6), 4) = 4.0 sec/part
5 kW: Part handling time = Max((0.3 × ((278 + 437 + 16.3) / 25.4) - 4.6), 4) = 4.0 sec/part

Pallet handling time is the time required to move a racked batch of parts both to and from the furnace. The time is dependent on plant layout. For costing purposes, we will assume that the furnace is located within 50 feet of the other manufacturing operations, and that the truck can be moved by hand at a speed of 1 foot/second, we estimate the total truck handling time for a batch as:

1 kW: Pallet handling time = ((2 × 50 feet/run) / 1 ft/sec.) × 2 runs/batch / 250 parts/batch = 0.8 sec/part
5 kW: Pallet handling time = ((2 × 50 feet/run) / 1 ft/sec.) × 4 runs/batch / 250 parts/batch = 1.6 sec/part

Total labor cost per part for material handling is:

1 kW: Handling cost per part = ((4.0 + 0.8) sec/part / 3600 sec/hr) × $45.00/hr / 0.85 = $0.071/part
5 kW: Handling cost per part = ((4.0 + 1.6) sec/part / 3600 sec/hr) × $45.00/hr / 0.85 = $0.082/part

The energy required to heat the oven at the start of a batch run can be calculated using the heat equation: $\Delta Q=\rho v c_p \Delta T$. The stacks are composed of about half and half stainless steel. The ceramic material has a specific heat of about 0.65 J/g-K at 1000°C, and material density is 6.1 g/ cm^3. Stainless steel has a specific heat of about 0.5 J/g-K, and material density is 8.0 g/ cm^3. We can estimate the mix of parts to exhibit a specific heat of about 0.58 J/g-K at 1000°C, and material density is 7.0 g/ cm^3 for the purposes of heating calculations. The total material volume per batch of parts is:

1 kW: Batch part volume $= 192 \times 6{,}584 = 1.26 \times 10^6$ cm^3
5 kW: Batch part volume $= 73 \times 24{,}922 = 1.45 \times 10^6$ cm^3

The energy required to heat the SOFC stacks is:

> 1 kW: Heating energy = 7.0 g/cm^3 × 1.26 × 10^6 cm^3 × 0.58 J/g-°C × 775°C × 2.8 × 10^{-7} kW-hr/j = 1110 kW-hr
> 5 kW: Heating energy = 7.0 g/cm^3 × 1.45 × 10^6 cm^3 × 0.58 J/g-°C × 775°C × 2.8 × 10^{-7} kW-hr/j = 1277 kW-hr

The time required to heat the parts to firing temperature, assuming 90% heating efficiency is:

> 1 kW: Heating time = 1110 kW-hr / (92 × 0.9) kW = 13.4 hours
> 5 kW: Heating time = 1277 kW-hr / (92 × 0.9) kW = 15.4 hours

The cost per part to heat the furnace is:

> 1 kW: Heating cost per part = 92 kW × 13.4 hr × \$0.07/kW-hr / 192 parts = \$0.449/part
> 5 kW: Heating cost per part = 92 kW × 15.4 hr × \$0.07/kW-hr / 73 parts = \$1.359/part

Data sheets obtained from industrial furnace manufacturer Yuxiang indicate that the power input required to maintain heat in high temperature furnaces is approximately 50% of the power used to raise the temperature. Thus, the cost per part to maintain the furnace at firing temperature is:

> 1 kW: Firing cost per part = (92 × 0.5) kW × 3 hours × \$0.07/kW-hr / 192 parts = \$0.050/part
> 5 kW: Firing cost per part = (92 × 0.5) kW × 3 hours × \$0.07/kW-hr / 73 parts = \$0.132/part

Cooling is generally done via natural or forced air convection. Forced air cooling via a blower and plenum system could be used. Blowers for furnaces of this size will generally require motors rated at 5 HP (3.73 kW) or less, and costing about \$0.26/hour to run, making the per part cost of cooling negligible. Assuming that total cool-down time is approximately equal to the heating time, the machine cost per part for the furnace is

> 1 kW: Machine cost per part = (3 + (2 × 13.4)) hours/run × \$25.00/hr / 192 parts/run / 0.85 = \$4.565/part
> 5 kW: Machine cost per part = (3 + (2 × 15.4)) hours/run × \$25.00/hr / 73 parts/run / 0.85 = \$13.618/part

A.11 Testing and Conditioning Process

Model Approach

- Test and condition fuel cell stack

Process Flow

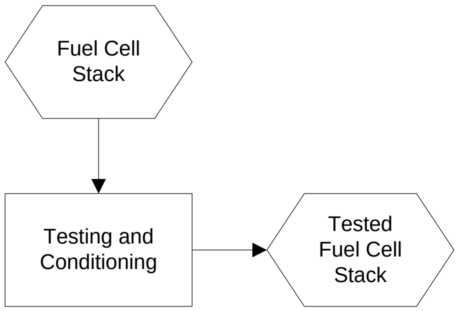


Figure A-11. Stack Brazing Process

Background

Following assembly, the SOFC stack is tested and conditioned to determine its fitness for installation into an APU system. The total test time is assumed to be 6 hours, consisting of a 2 hour warm-up at 5% hydrogen (H_2)/95% nitrogen (N_2), a 2 hour test at 50% H_2/50% N_2, and 2 hour cool-down at 100% N_2. Total H_2 consumption at full power is:

1 kW: 15 l/min
5 kW: 71 l/min

Preliminary Analysis

Assuming setup and teardown of the stack test stand requires 1 hour for 1 operator per run, the setup cost per stack is:

Setup cost per part = 1 hour $\times$ \$45/hour / 0.85 = \$52.94/stack

Internet consensus for the cost of hydrogen in bulk estimated is \$4/kg. The mass of 1 mole hydrogen gas (H_2) = 2 grams, so the mass of 22.4 liters (stp) of H_2 is 2 g.

1 kg of H_2 = (1000 / 2) $\times$ 22.4 liters = 11,200 liters = 11.2 m^3
Cost of H_2 = \$4/kg / 11.2 m^3/kg = \$0.357/m^3

Atlas Copco, in an article for Pharmaceutical Processing, provides a cost of on-site generated nitrogen (N_2) of about \$0.21/100ft^3 (\$0.074/m^3)

1 kW: Total flow rate = 30 l/min $\times$ 60 min/hr / 1000 l/ m^3 = 1.8 m^3/hr
5 kW: Total flow rate = 142 l/min $\times$ 60 min/hr / 1000 l/ m^3 = 8.52 m^3/hr

During the 2 hour warm-up, the total material cost of the fuel gas is

1 kW: Warm-up material cost = $(((1.8 \times 0.95)\ m^3/hr \times \$0.074/m^3) + ((1.8 \times 0.05)\ m^3/hr \times \$0.357/m^3)) \times 2\ hrs = \$0.317/stack$
5 kW: Warm-up material cost = $(((8.52 \times 0.95)\ m^3/hr \times \$0.074/m^3) + ((8.52 \times 0.05)\ m^3/hr \times \$0.357/m^3)) \times 2\ hrs = \$1.502/stack$

During the 2 hour full power test, the total material cost of the fuel gas is:

1 kW: Full power material cost = $(((1.8 \times 0.50)\ m^3/hr \times \$0.074/m^3) + ((1.8 \times 0.50)\ m^3/hr \times \$0.357/m^3)) \times 2\ hrs = \$0.776/stack$
5 kW: Full power material cost = $(((8.52 \times 0.50)\ m^3/hr \times \$0.074/m^3) + ((8.52 \times 0.50)\ m^3/hr \times \$0.357/m^3)) \times 2\ hrs = \$3.672/stack$

During the 2 cool-down, the total material cost of the fuel gas is:

1 kW: Cool-down material cost = $1.8\ m^3/hr \times \$0.074/m^3 \times 2\ hrs = \$0.266/stack$
5 kW: Cool-down material cost = $8.52\ m^3/hr \times \$0.074/m^3 \times 2\ hrs = \$1.261/stack$

Total material cost for a full test and conditioning cycle is:

1 kW: Testing material cost = 0.317 + 0.776 + 0.266 = $1.359/stack
5 kW: Testing material cost = 1.502 + 3.672 + 1.261 = $6.435/stack

We will assume that 1 operator can cover 3 testing stations, making the total labor cost:

Testing labor cost = 0.33×6 hrs/stack * $45.00/hr / 0.85 = $104.82/part

Total machine cost per part is:

Testing machine cost = 6 hrs/stack * $25.00/hr / 0.85 = $176.47/part

A.12 Assembly Cost Learning Curve Calculations

The DFMA™ software produces and assembly cost based on hand assembly at its most efficient, which is $11.78 for the 1 kW stack, $20.76 for the 5 kW stack, and $94.65 for the rest of the system. The learning curve analysis essentially backs that number up to a time when bugs are still being worked out of the assembly process.

From Cost Estimator's Reference Manual, Stewart, R.M., et al, 2nd Ed., Wiley-Interscience, 1995, the general equation is:

$$Y = AX^b$$

where:

Y = time or cost per cycle or unit
A = time or cost for first cycle or unit
X = number of cycles or units
b = log(m)/log(2)

$$m = \text{slope of learning curve}$$

For stack assembly cost, if we assume that m = 0.85 (typical for aerospace processes), then:

$$b = \log(0.85)/\log(2) = -0.23447$$

If the stack assembly process is "learned" after 100 units, and the cost of the $X = 100^{th}$ stack is the BDI DFA cost, then the cost of the first unit is:

1 kW: $A = Y / X^b = 11.78 / 100^{(-0.23447)} = \$34.68$
5 kW: $A = Y / X^b = 20.76 / 100^{(-0.23447)} = \$61.12$
System: $A = Y / X^b = 94.65 / 100^{(-0.23447)} = \$278.64$

The average cost to assemble the first 100 units ($\overline{C}_{100}$) is calculated as:

$$\text{1 kW: } \overline{C}_{100} = \frac{\left(\sum_{i=1}^{100} 148.14 * \mathrm{i}^{(-0.23447)}\right)}{100} = \$15.17$$

$$\text{5 kW: } \overline{C}_{100} = \frac{\left(\sum_{i=1}^{100} 154.47 * \mathrm{i}^{(-0.23447)}\right)}{100} = \$26.74$$

$$\text{System: } \overline{C}_{100} = \frac{\left(\sum_{i=1}^{100} 132.30 * \mathrm{i}^{(-0.23447)}\right)}{100} = \$121.92$$

The cost to assemble all subsequent units is assumed to be A, making the average cost to assemble n units (n > 100) is calculated as:

$$\overline{C}_{n} = \frac{\left(\left(\sum_{i=1}^{100} \mathrm{A} * \mathrm{i}^{(-0.23447)}\right) + \left(A * (n - 100)\right)\right)}{n}$$

Using the above equations, the average stack assembly costs are:

1st Year Average Assembly Cost per Stack			
	Stacks per year		
	100	1000	10000
1 kW Stack	15.17	12.12	11.81
5 kW Stack	26.74	21.36	20.82
System	121.92	97.38	94.92

A.13 ATR General Design

The diesel ATR reformer will be comprised of a catalyst coated monolithic reactor encased in a tubular shell, along with a diesel fueled startup heater.

The tubular design will incorporate multiple regions to facilitate adequate vaporization, mixing and conversion to the incoming reactants, as shown in Figure A-12. The reactor monolith will be supported by a ceramic mat common to automotive catalytic converters.

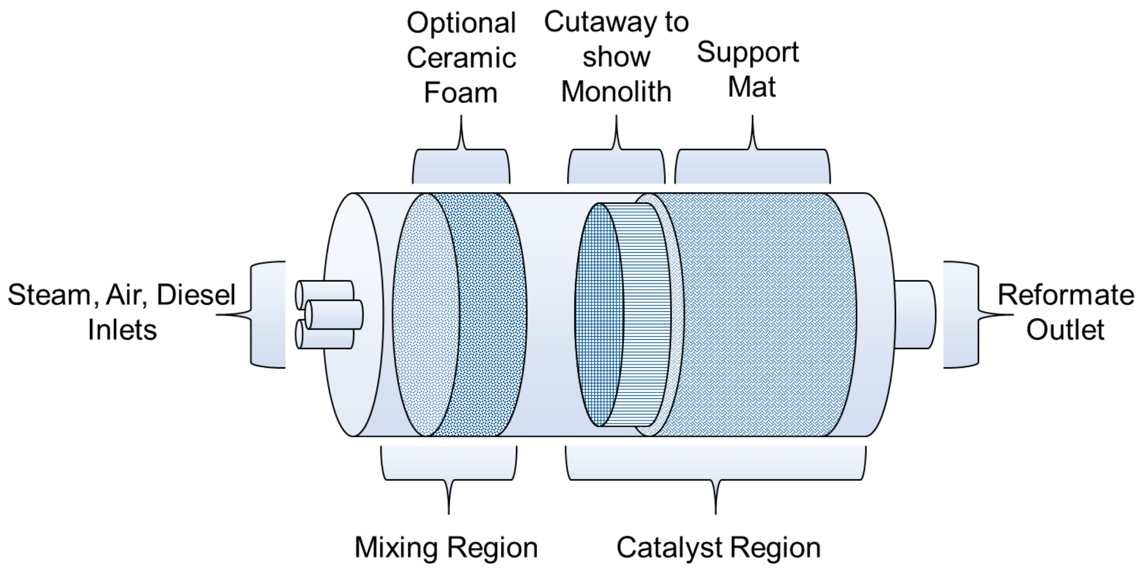


Figure A-12. ATR General Design

The size of the reformer for the two systems is as follows:

- 1kW: 2.25” ID x 8”L (.25” over monolith OD for the mat and 3” longer for the mixing zone)
- 5kW: 3.75” DIA x 12”L (.25” over monolith OD for the mat and 3.75” longer for the mixing zone)

ATR Materials

- Mixing Foam
  - Al2O3 high porosity foam disc
    - 1kW size: 2.25”DIA x 1” cylinder
    - 5kW size: 3.75”DIA x 1.5” cylinder
- Cordierite Monolith
  - 400 cells per square inch (cpsi) extruded cordierite
    - 1kW: 2”DIA x 5” cylinder
    - 5kW: 3.5”DIA x 8.25” cylinder

- Catalyst
  - Research indicates improved diesel reforming performance from noble metal catalysts (over traditional Ni catalyst) to reduce carbon formation and increase sulfur tolerance;

Platinum, Rhodium and Ruthinium most commonly used[41]. Pt is prone to carbon formation and sintering issues at these temperatures (800+°C) and Ru is not really vetted for diesel ATR – though it is significantly cheaper and a potential candidate for diesel ATR with more testing. Rh has good performance in both POX and SR, therefore ideal for ATR[42]. Common support substrates are metal oxides such as Al_2O_3, CeO_2, ZrO_2, SiO_2 and TiO_2. Al_2O_3 is most common in diesel ATR lab designs, but has a tendency to sinter at high temperatures, lose surface area and has only a moderate bond with the noble metal unless a separate binder component is used. CeO_2 doped with Gd provides excellent oxygen transport, improved resistance to carbon deposition, and excellent metal bonding properties[43]. (proven catalyst performance for diesel ATR is area with least consistent published data, also extensively used in SOFC anode layer for ionic transport poroperties)

- Catalyst composition: 3%Rh/GDC (Gadolinium doped Cerium Oxide) 15% wt of monolith
    - Rh quantity (estimates)
        - 1 kW: 0.88 grams
        - 5 kW: 4.46 grams
    - GDC Quantity (estimates)
        - 1 kW: 28.47 grams
        - 5 kW: 144.26 grams

- Ceramic support mat
    - There is a significant difference in the thermal expansion coefficient of the ceramic monolith and the steel shell. Additionally, isolation from shock and vibration increase the life of the reformer. In automotive catalytic converters, the expansion layer is composed of alumina-silicate fibers, vermiculite adhered with organic bonder. SiO is a potential poison for SOFC cells, so straight Al_2O_3 mat will be used with ceramic binder to limit gas bypass flow.
    - Alumina SiO mat wrapped around monolith wall
        - 1kW: 5” x 6.25”
        - 5kW: 8.25” x 11”
- Canning
    - Contents are packaged/canned with simple sheet metal construction. Typically, high temperature stainless or Inconel used. Size is large enough to secure monolith and support mat, with additional volume for mixing region
    - Material
        - Inconel 625 chosen for high temperature resistance
            - Coil sheet cost: $60/kg

[41] P Cheekatamarla, CM Finnerty, Reforming catalysts for hydrogen generation in fuel cell applicaions. Journal of Power Sources 160 (2006) 490-499

[42] X Karatzas, D Creaser, A Grant, J Dawody, L Pettersson, Hydrogen generation from n-tetradecane, low-sulfur and Fischer-Tropsch diesel over Rh supported on alumina doped with ceria/lanthana. Catalysis Today 164 (2011) 190-197

[43] S Yoon, J Bae, A diesel fuel processor for stable operation of solid oxide fuel cells system. Catalysis Today 156 (2010) 49-57

    - Round bar stock cost: $100/kg
    - Pipe cost: $225/kg
    - Scrap value = $14.09/kg
- Low internal pressure –2mm wall thickness is adequate for ATR body
    - Compromise between weight and necessary thickness for welding end caps
- End caps designed to accept threaded fittings
    - 12mm thickness allows sufficient thread depth for 0.25" and 0.625" fittings
    - Machined flange to allow 1mm clearance with tube ID and 6mm excess on OD for welding

ATR Startup Heater General Design

The ATR startup heater chosen for analysis is a proprietary burner design consisting of a fuel vaporizer, air mixing chamber and igniter, as shown in Figure A-13. This burner was specifically designed to vaporize and then combustion in gas phase a diesel or kerosene type fuels. The vaporizer is relatively easy to clean in case of coking. Therefore, this burner represents a high confidence design for which detailed drawings were available. Alternative approachs would likely be less expensive, if perhaps more difficult to maintain: this design yields a conservative cost estimate and is therefore adequate for this purpose.

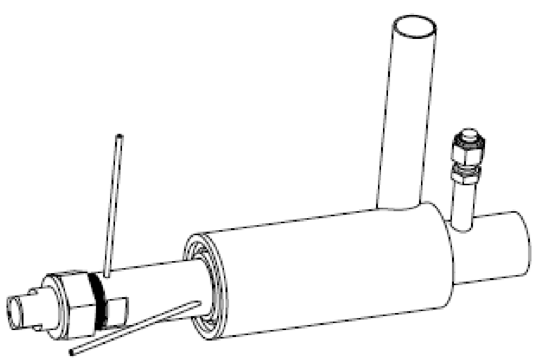


Figure A-13. ATR Startup Burner

The heater is manufactured using 316 and 304 stainless steel with material costs as follows:

- 316 Stainless Steel
    - Coil sheet cost: $6.69/kg
    - Round bar stock cost: $16.39/kg
    - Pipe cost: $32.77/kg
    - Scrap value = $1.54/kg
- 310 Stainless Steel
    - Coil sheet cost: $15.70/kg
    - Round bar stock cost: $31.40/kg
    - Pipe cost: $62.79/kg
    - Scrap value = $3.21/kg

Heater manufacturing processes include turning, milling, sheet metal forming, drilling and tapping, and welding. All processes and final assembly were modeled using the Boothroyd-Dewhurst DFMA^{TM} software.

DFMA^{TM} Trade-off Analysis for ATR Canning

The Boothroyd-Dewhurst DFMA^{TM} software tool was used to perform a trade-off analysis of three potential canning designs:

- Pipe
- Seam-welded tube from sheet metal
- Seam-welded tapered body from sheet metal

Manufacturing and assembly parameters used to perform the analysis were as follows:

- Life volume = 100,000 parts
- Batch volume = 10,000 parts
- Sheet metal die life = 400,000 parts
- Labor rate = $45.00/hr
- Machine cost = $25.00/hr
- Overall plant efficiency = 85%

Pipe Design

The layout for the ATR can pipe design in shown in Figure A-14.

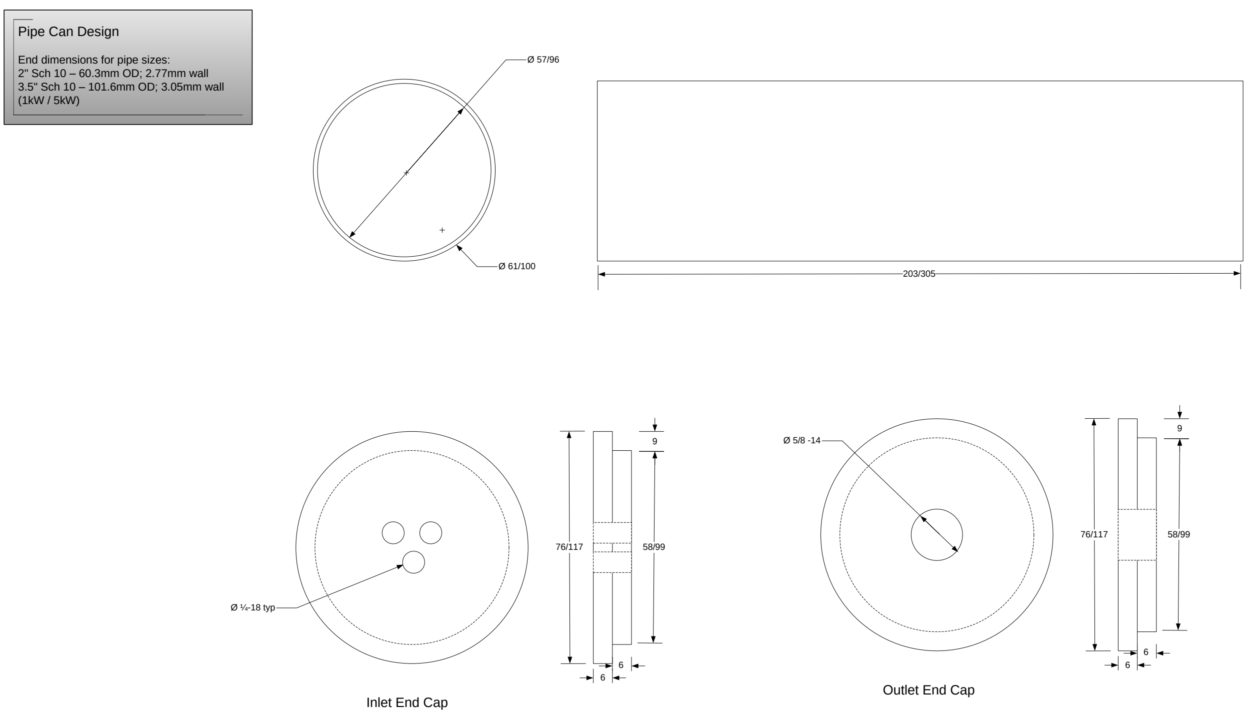


Figure A-14. ATR Can – Pipe Design Layout

- Fabrication process

    - 2"/3.5" Sch 10 pipe to form ATR body
        - Cut to length
        - Break edges
    - Machined end caps from round bar stock
        - Cut to length
        - Turn flange step
        - Drill and tap
    - Install wrapped, catalyzed monolith and ceramic foam
    - Install and inert gas weld end caps
- Advantage
    - Straight tube geometry
    - Use of pre-fabricated tube for body eliminates manufacturing and assembly steps
- Disadvantage
    - High cost of pre-fabricated tube
    - Larger end caps = higher cost and weight
- Costs (w/o catalyzed monolith, ceramic foam)
    - 1 kW: $329.15
    - 5 kW: $866.27

Seam-welded Tube from Sheet Metal

The layout for the ATR can seam-welded tube design in shown in Figure A-15.

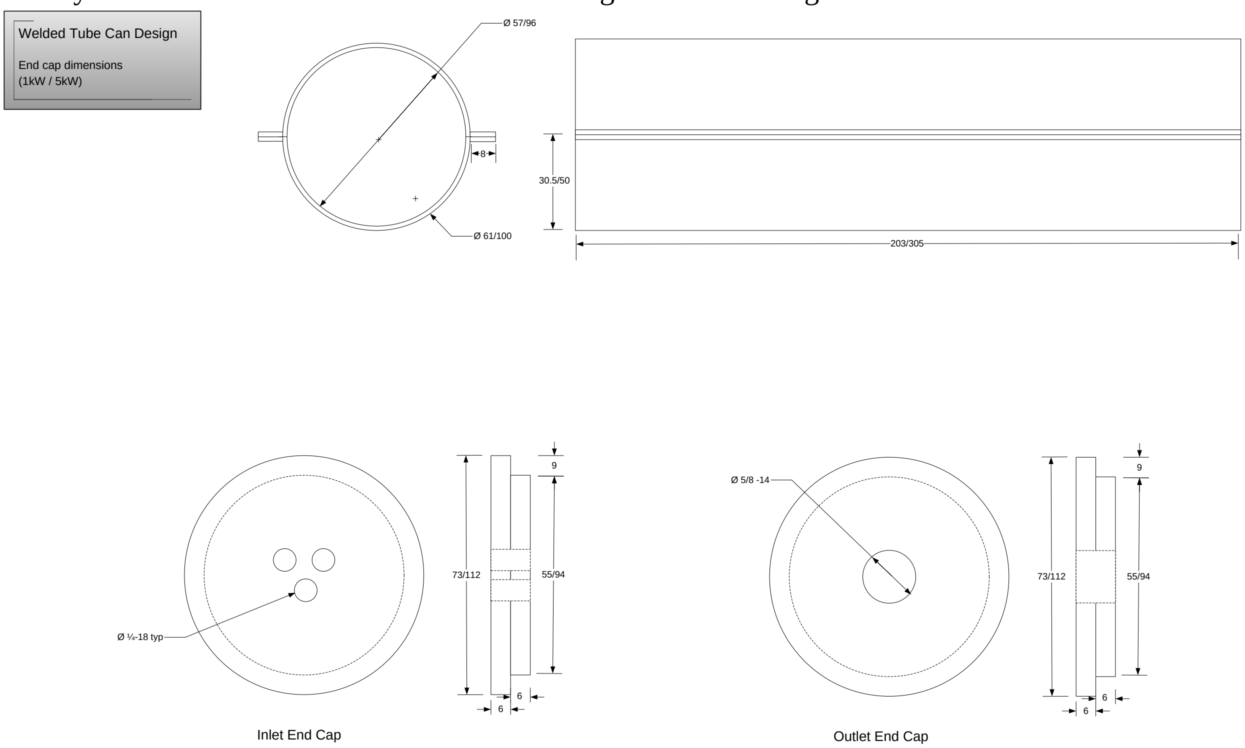


Figure A-15. ATR Can – Seam-welded Tube Design Layout

- Fabrication process
    - Coil-fed stamping and bending
        - Blank half shell from sheet
        - Form seam bends

- Roll bend to half cylinder
  - Machined end caps from round bar stock
    - Cut to length
    - Turn flange step
    - Drill and tap
  - Install wrapped, catalyzed monolith and ceramic foam in lower half shell
  - Resistance seam weld upper half shell
  - Install and inert gas weld end caps
- Advantage
  - Straight tube geometry
- Disadvantage
  - Larger end caps = higher cost and weight
  - More complex assembly process
- Costs (w/o catalyzed monolith, ceramic foam)
  - 1 kW: $172.58
  - 5 kW: $375.63

Seam-welded Tapered Body from Sheet Metal

The layout for the ATR can seam-welded tapered body design in shown in Figure A-16.

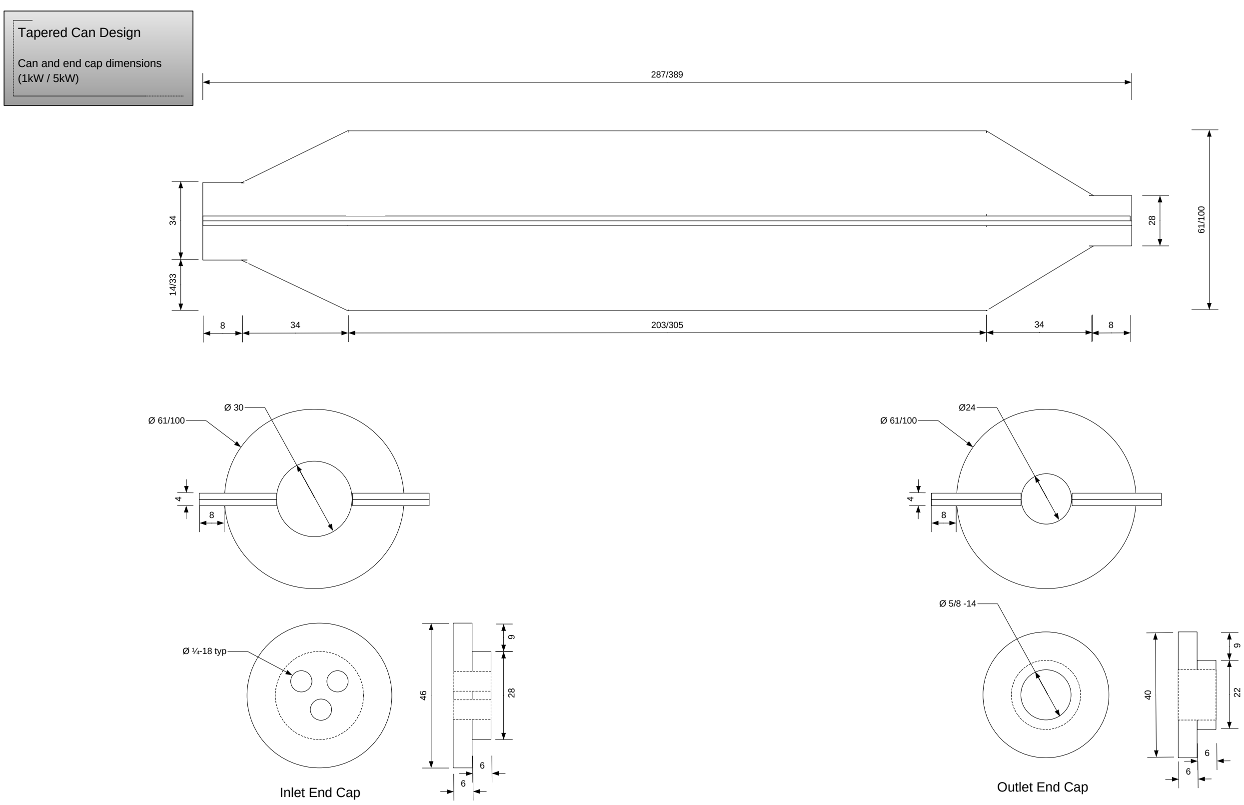


Figure A-16. ATR Can – Seam-welded Tapered Body Design Layout

- Fabrication process
  - Coil-fed stamping and bending

        - Blank half shell from sheet
        - Form seam bends
        - Form tapered half cylinder
    - Machined end caps from round bar stock
        - Cut to length
        - Turn flange step
        - Drill and tap
    - Install wrapped, catalyzed monolith and ceramic foam in lower half shell
    - Resistance seam weld upper half shell
    - Install and inert gas weld end caps
- Advantage
    - Smaller end caps
- Disadvantage
    - More complex manufacturing and assembly process
- Costs (w/o catalyzed monolith, ceramic foam)
    - 1 kW: $135.97
    - 5 kW: $212.61

A.14 Desulfurizer Design

The desulfurizer is a zinc oxide filled tube constructed from 316 stainless steel pipe with welded end caps, similar to the pipe design for the ATR reactor described in Section A.13. The desulfurizer for the 1 kW system is 1" diameter by 3" long, and for the 5 kW system is 1.5" diameter by 6" long.

- Fabrication process
    - 1"/1.5" Sch 10 pipe to form ATR body
        - Cut to length 3"/6"
        - Break edges
    - Machined end caps from round bar stock
        - Cut to length
        - Turn flange step
        - Drill and tap
    - Install and inert gas weld inlet cap
    - Fill tube with zinc oxide pellets
    - Install and inert gas weld outlet cap

The material costs used in the analysis are as follows:

- 316 Stainless Steel
    - Coil sheet cost: $6.69/kg
    - Round bar stock cost: $16.39/kg
    - Pipe cost: $32.77/kg
    - Scrap value = $1.54/kg