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Stationary and Emerging Market Fuel Cell System Cost Analysis – Auxiliary Power Units FC097

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Battelle

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Washington D.C.

Overview – Program Details

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Timeline		
Start		End
Oct 2011	FY13 (BP2)	Sep 2016

Total Funding Spent $765.9K as of 3/31/14

Budget (DOE Project Funding)	
$250K FY13 Funding	Total $2 M

FY14 Funding $486K

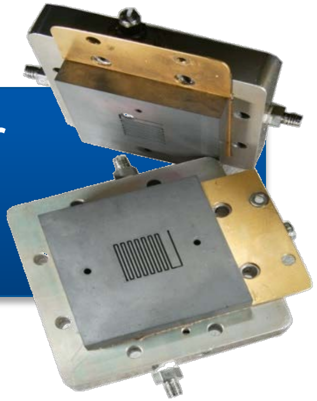
Collaborators

have provided design inputs, cost inputs, design review, and manufacturing cost review

- Hydrogenics
- NexTech
- Ballard
- Crown
- Delphi
- Nuvera
- Bulk Molding Compounds
- American Durafilm
- Metro Mold and Design
- 3M
- SonoTek
- PCI
- AllCell Technologies

Barriers Addressed		
Cost reduction of fuel cell components and materials	Manufacturing capability	Customer acceptance

Relevance – Program Objective



5-year program to assist DOE in developing fuel cell systems for stationary and emerging markets by developing independent models and cost estimates

- Applications - Primary (including CHP) power, backup power, APU, and material handling equipment
- Fuel Cell Types - 80°C PEM, 180°C PEM, SOFC technologies
- Annual Production Volumes - 100, 1K, 10K and 50K (only for primary production systems)
- Size - 1, 5, 10, 25, 100, 250 kW

In Budget Period 2 (BP2)

- 1 and 5 kW SOFC for Auxiliary Power Unit (APU) applications
- 1 and 5 kW PEM for Material Handling Equipment (MHE) applications

Relevance – Technical Barriers Addressed

Technical Barriers	Project Goals
Cost reduction of fuel cell components and materials	1. Identify major contributors to fuel cell system cost 2. Quantify potential cost reduction based upon technological improvements
Manufacturing capability	3. Identify major contributors to fuel cell system manufacturing cost 4. Identify areas for manufacturing R&D to improve quality and/or throughput 5. Provide basis for consideration of transition from other industries
Customer acceptance	6. Develop accurate cost projections that can be used to evaluate total cost of ownership and facilitate early market adoption

Approach – Manufacturing Cost Analysis Methodology

Market Assessment

- Characterization of potential markets
- Identification of operational and performance requirements
- Evaluation of fuel cell technologies relative to requirements
- Selection of specific systems for cost modeling

System Design

- Conduct literature search
- Develop system design
- Gather industry input
- Size components
- Gather stakeholder input
- Refine design
- Develop bill of materials (BOM)
- Define manufacturing processes
- Estimate equipment requirements

Cost Modeling

- Gather vendor quotes
- Define material costs
- Estimate capital expenditures
- Determine outsourced component costs
- Estimate system assembly
- Develop preliminary costs
- Gather stakeholder input
- Refine models and update costs

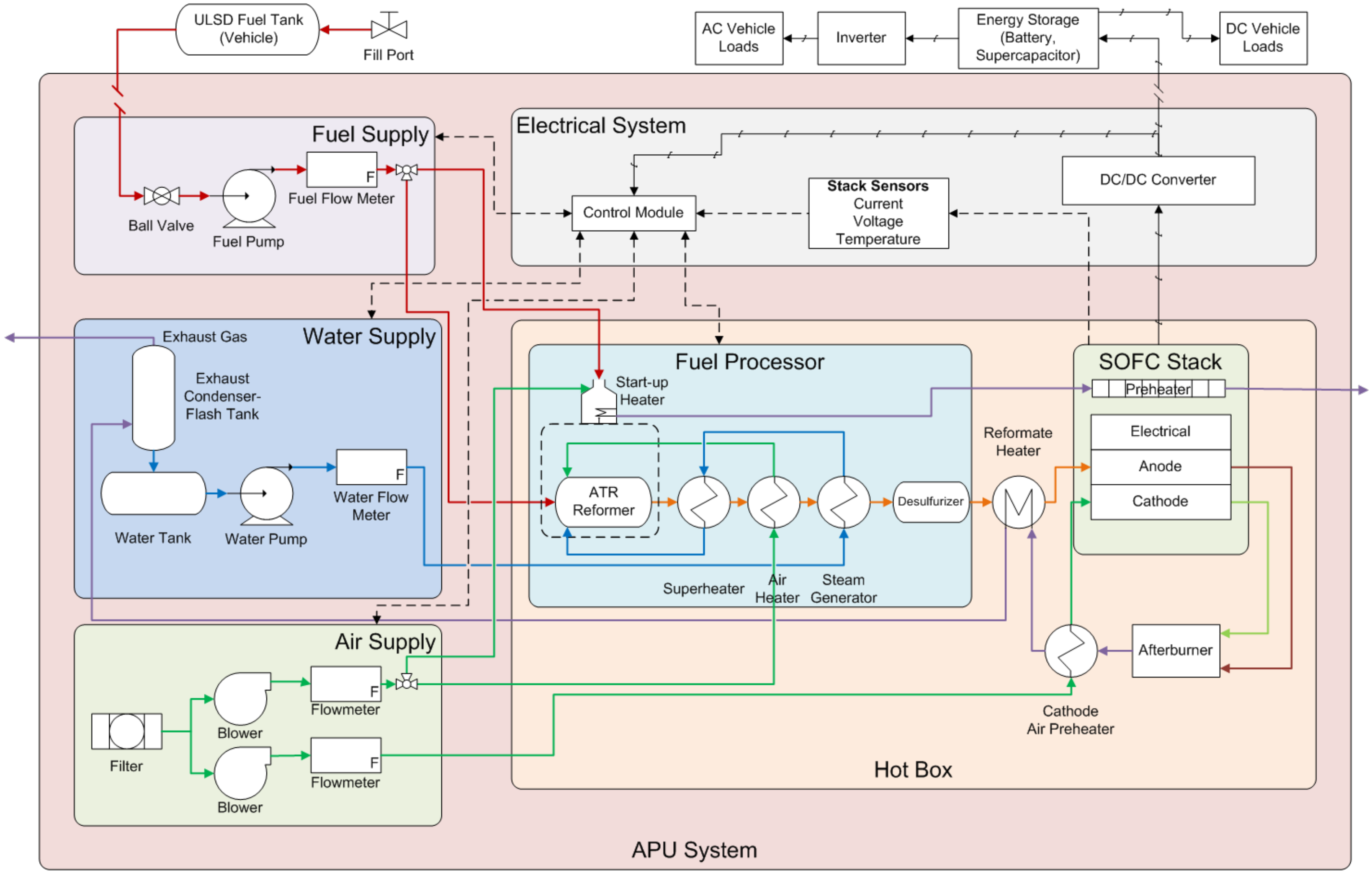
Sensitivity & Life Cycle Cost Analysis

- Sensitivity analysis of individual cost contributors
- Life cycle cost analysis to estimate total cost of ownership

Progress & Accomplishments – BP2

- Completed the manufacturing cost analysis for SOFC fuel cells for APU applications
  - Presented these results at the Fuel Cell Seminar
- Completed the manufacturing cost analysis for small PEM systems for MHE applications

Progress & Accomplishments – SOFC Fuel Cell System Design for APU Applications



Progress & Accomplishments – Additional Design Details

Component	Specification
Fuel (Anode)	• ULSD (appox 15 ppm Sulfur, EPA regulated) • Reformed and desulfurized to <0.1 ppmv sulfur and <1% hydrocarbons • Fuel supplied from onboard diesel tanks • No input water • Air filtered for particulates and chemicals (passive)
Air (Cathode)	• Filtered for particulates and chemicals (passive) • Flow is 2X stoichiometric
Electric	• 12 VDC regulated output • Buck DC/DC converter • 1 kW hybridized system with on-board truck battery to supply short bursts of peak power
General	• 10,000 hr lifetime • < 2% degradation per 1000 hours of operation • 30% Electrical efficiency at rated power(Complete System)

Progress & Accomplishments – APU SOFC Fuel Cell System Specification

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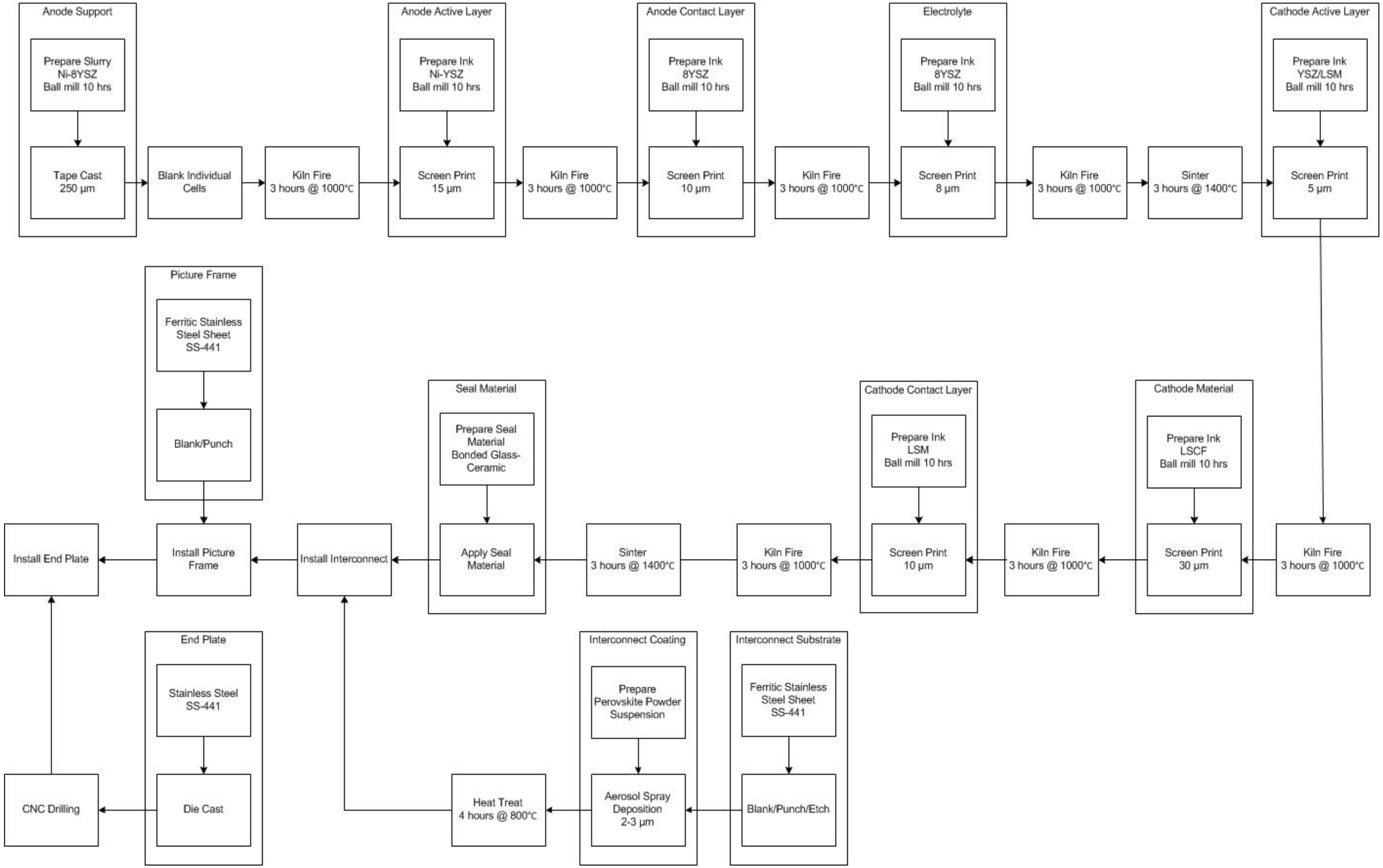
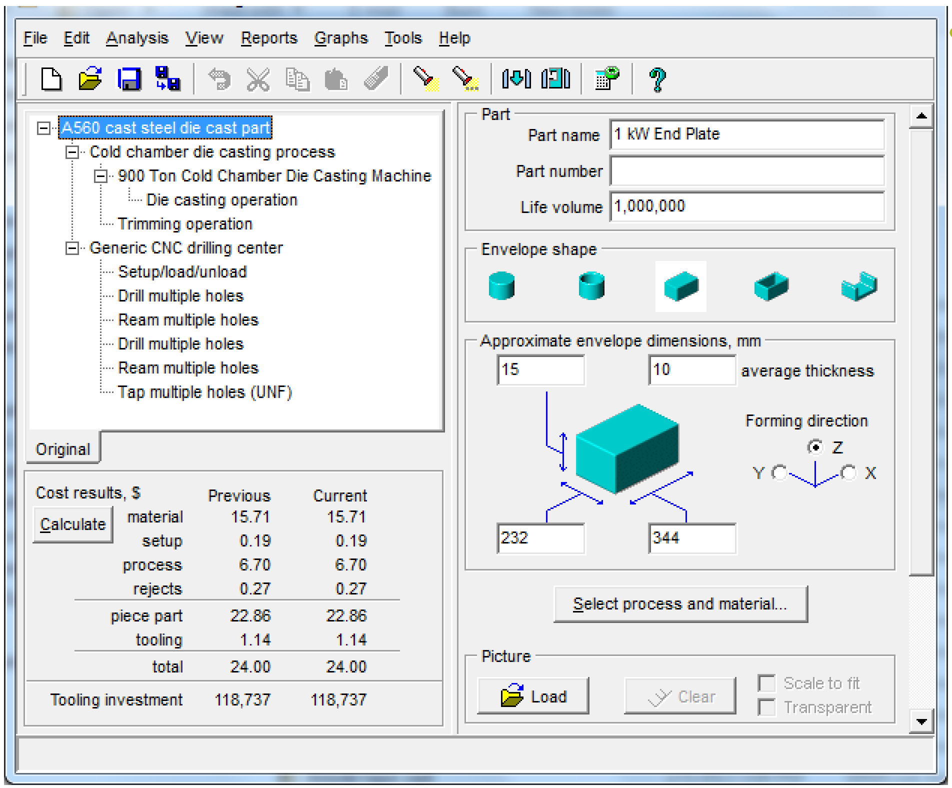
Parameter	1kW System	5kW System
Power Density (W/cm^2)	0.32	
Current Density (A/cm2)	0.4	
Cell Voltage (VDC)	0.8	
Active Area Per Cell (cm2)	200	500
Net Power (kW)	1	5
Gross Power (kW)	1.22	6.08
Number of Cells (#)	19	38
Full Load Stack Voltage (VDC)	15.2	30.4
Cell Design	Planar, Anode supported	
Anode Application	Ni-8YSZ, 250 µm thick, tape cast, kiln fired	
Subsequent Cell Layer Application	5-30 µm thick, screen print, kiln fire	
Seals	Wet application bonded glass ceramic	
Interconnects	Ferritic Stainless Steel (SS-441) with Perovskite coating, 2-3 µm thick	
End plates	A560 cast steel	
Stack Assembly	Hand assembled, tie rods, furnace braze	
Test and Condition	2 hr. warm-up 5% H_2/95% N_2, 2 hr. test 50% H_2/50% N_2, 2 hr. cool down 100% N	

Progress & Accomplishments – SOFC Fuel Cell Stack Manufacturing Process Overview



Progress & Accomplishments – Methodology for Calculating Manufacturing Costs

- Use the Boothroyd-Dewhurst DFMA® estimating software for standard process models whenever they exist
- Developed custom models as needed



- Custom Model Development Process
  - Develop model approach and process flow
  - Perform preliminary model analysis
    - Inputs and calculations required to produce cost outputs
    - Independent verification of viability and accuracy
  - Implement model in Excel
    - Develop model using DFMA principles and methods
    - Validate model results against preliminary cost analysis results

Progress & Accomplishments – Manufacturing Processes Evaluated

Process	Method Evaluated	Alternatives Not Evaluated
Ceramic Deposition	Screen Printing Tape Casting	• Plasma Spray Coating
Interconnect	Sheet Metal Stamping Etching Spray Deposition Coating	• Laser Cutting • Water Jet Cutting • Chemical Etching
Sealing	Bead Deposition	• Screen Printing • Tape Casting
Picture Frame	Sheet Metal Stamping	• Laser cutting • Injection molding
End Plate	Die Casting	• Machining • Stamping, Welding

Progress & Accomplishments – Major Stack Material & Process Assumption

Material	Cost ($)	Measure
NiO	32	kg
8YSZ	50	kg
Ni-YSZ	35	kg
LSM-YSZ	150	kg
LSCF	150	kg
Lanthanum Oxide	15	kg
Perovskite Coating	150	kg
441 Stainless Steel	5.31	kg
A560 Stainless Steel	5.64	kg

Process Assumptions	Value
Custom process scrap rate	3.0%
Standard process scrap rate	0.5%
Inspection steps included in processing	None
Labor cost	$45/hr
Machine cost*	$25/hr
Energy cost	$0.07/kW-h
Overall plant efficiency	85%
Operators per line	1

*note that energy cost of high power machines is included in processing cost

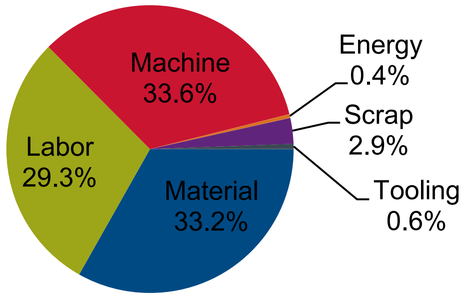
Progress & Accomplishments – Capital Cost Assumptions

Capital Cost	Unit Cost (2013$)	Units	Total Cost (2013$)	Assumption/Reference
Factory Total Construction Cost	250	$/sq ft	751,723 to 1,348,055	• 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		1,537,495 to 2,890,680	• Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks
Forklifts	25,000	$/lift	50,000	• Assumes 2 forklifts with extra battery and charger
Cranes	66,000	$/crane	198,000	• Assumes 3 cranes, 5 ton capacity, 20' wide per line
Real Estate	125,000	$/acre	125,000	• Assumes 1 acre of vacant land, zoned industrial Columbus, OH
Contingency	10% Capital Cost		266,222 to 461,174	• Construction estimation assumption
Total			**2,928,440 to 5,072,909**	• Varies with anticipated annual production volumes of both 1 kW and 5 kW stacks

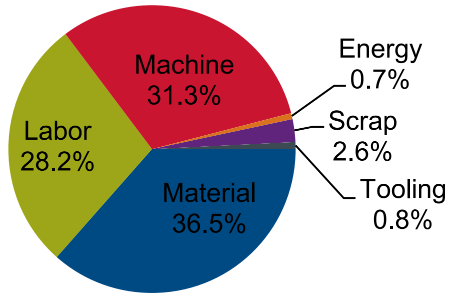
Progress & Accomplishments – 1 kW SOFC Stack Manufacturing Cost

Stack Component	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
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
Stack assembly	15	12	12	12
Stack brazing	3	6	6	6
Stack test and conditioning	353	353	353	353
Stack Total (less testing)	590	511	481	473

1 kW Stack - Cost by Category
100 stacks/year



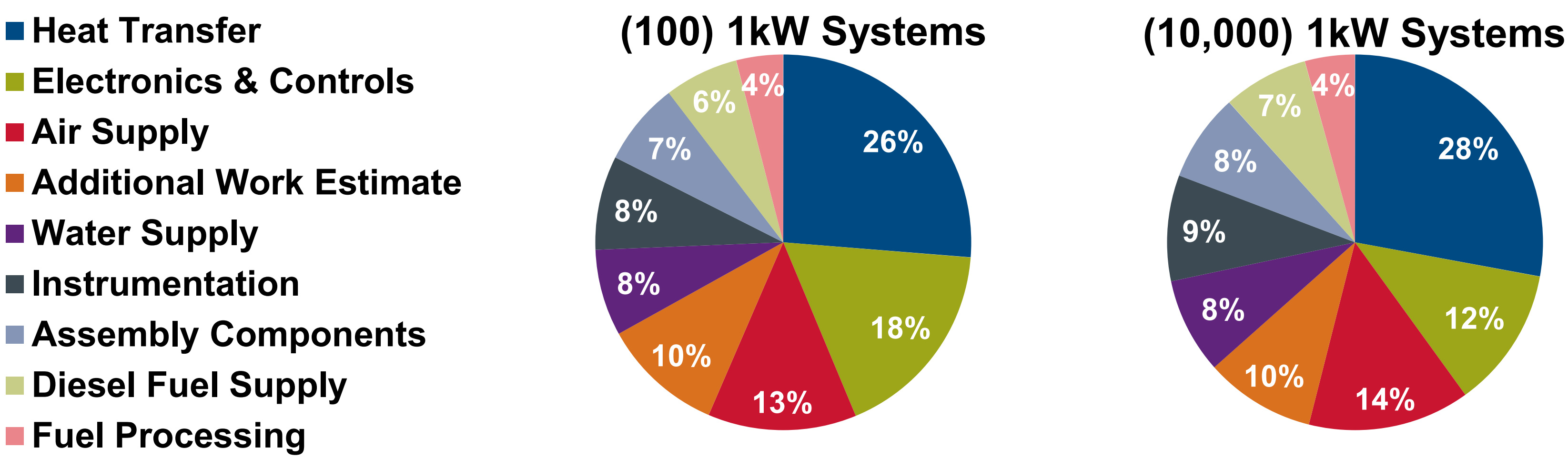
1 kW Stack - Cost by Category
50,000 stacks/year



All costs include manufacturing scrap

Progress & Accomplishments – 1 kW APU SOFC BoP Manufacturing Cost

BoP Components	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
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
BOP Total	9,597	8,205	7,383	7,383



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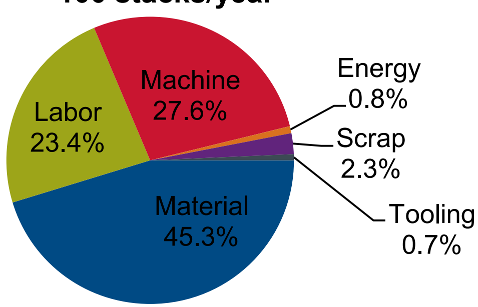
Progress & Accomplishments – 1 kW APU SOFC Fuel Cell System Cost Summary

Description	100 Units	1,000 Units	10,000 Units	50,000 Units
Total stack manufacturing cost, with scrap	$590	$511	$481	$473
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**

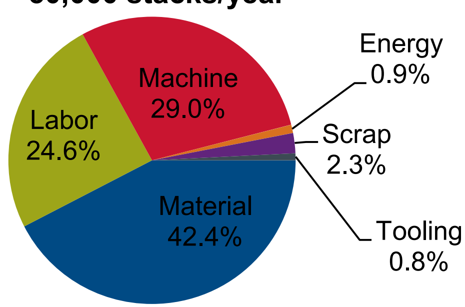
Progress & Accomplishments – 5 kW SOFC Stack Manufacturing Cost

Stack Component	100 Units ($/each)	1000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
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
Stack assembly	27	21	21	21
Stack brazing	12	16	16	16
Stack test and conditioning	359	359	359	359
Stack Total (less testing)	1,476	1,327	1,267	1,257

5 kW Stack - Cost by Category
100 stacks/year



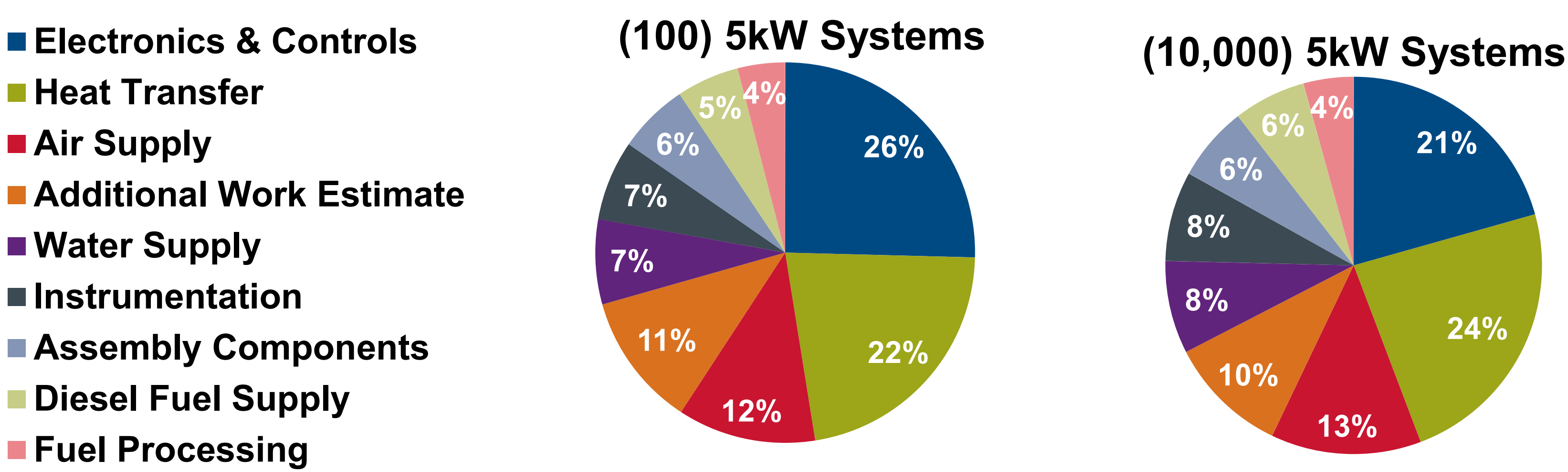
5 kW Stack - Cost by Category
50,000 stacks/year



All costs include manufacturing scrap

Progress & Accomplishments – 5 kW APU SOFC BoP Manufacturing Cost

BoP Components	100 Units ($/each)	1,000 Units ($/each)	10,000 Units ($/each)	50,000 Units ($/each)
Fuel Supply	610	542	542	542
Air Supply	1,342	1,160	1,128	1,128
Water Supply	825	737	696	696
Power Electronics & 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
BOP Total	11,323	9,802	8,738	8,738



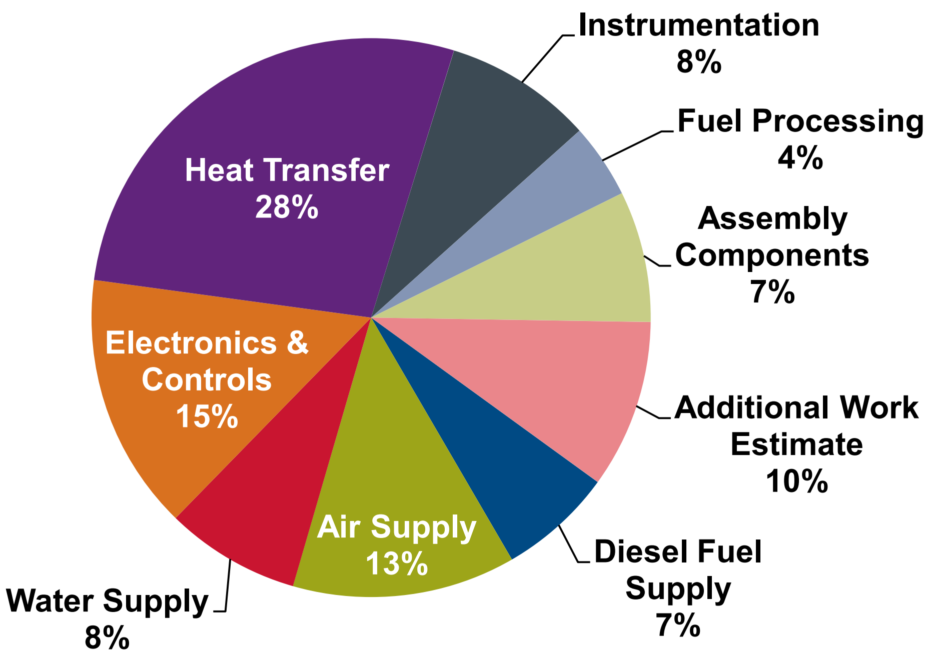
Progress & Accomplishments – 5 kW APU SOFC Fuel Cell System Cost Summary

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
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**

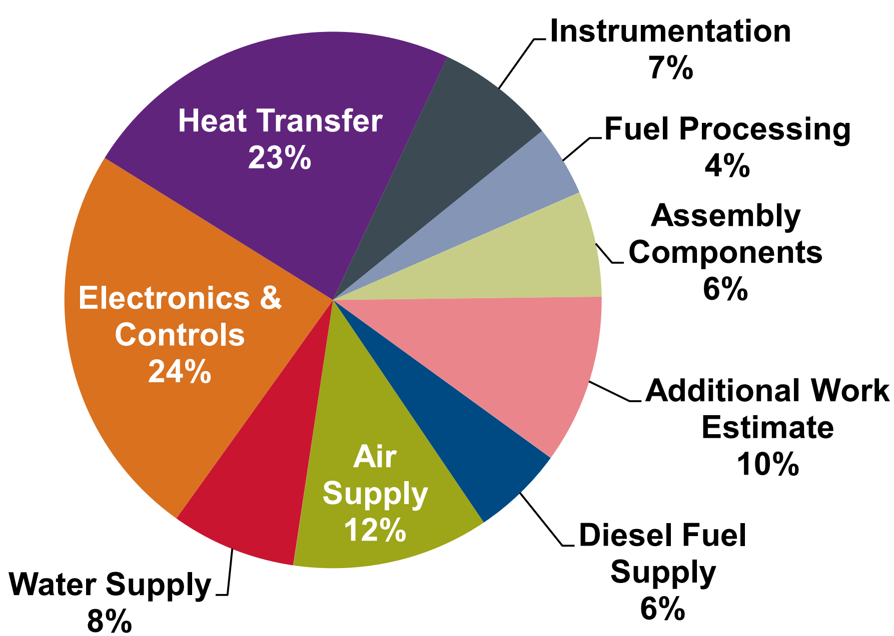
Progress & Accomplishments – APU SOFC BoP Cost Comparison

- 3 Dominant Cost Drivers
  1. Heat Transfer Components
  2. Electronics & Controls
  3. Air Supply

1kW Systems - 1000 units/yr



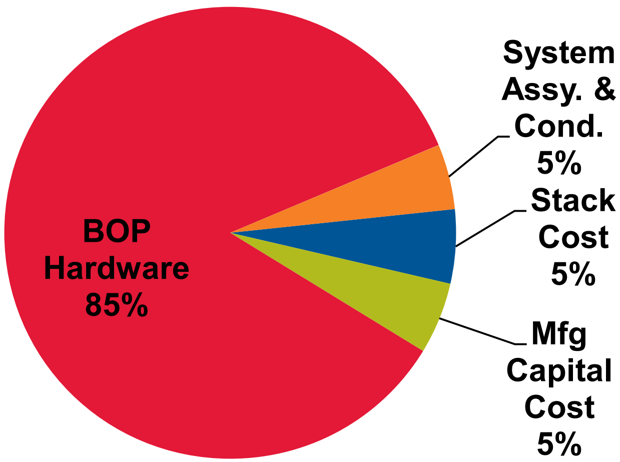
5kW Systems - 1000 units/yr



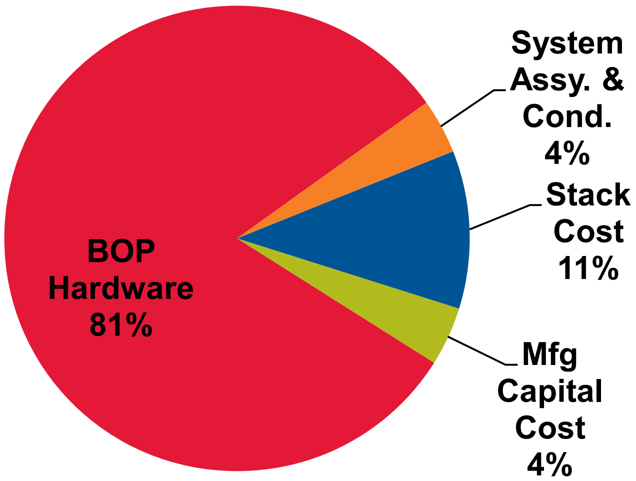
Progress & Accomplishments – APU System Cost Comparison

- Largest System Expense = Balance of Plant (BOP) Hardware
- Avenues for BOP Cost Reductions:
  - Improved heat exchanger manufacturing
  - Reduce number of heat exchangers in system
  - Eliminate DC/DC converter
  - Alternative make-up water management – Anode Gas Recirculation?

1 kW Units - 1000 units/yr



5 kW Units - 1000 units/yr



Progress & Accomplishments – Life Cycle Cost Analysis Assumptions

	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
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	Included in cost of system	$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

* Based on 10,000 units per year

Progress & Accomplishments – Results Summary

- Production volume has negligible effect on stack cost
  - Ceramic material and commodity cost constant across all volumes
  - Material processing requirements limit throughput
- Manufacturing Readiness Level (MRL) for many BOP components not ready for mass production – significant cost driver
  - DMFA performed on specific components (Reformer, Desulfurizer, Stack) assumes technology > MRL 9

Progress & Accomplishments –
Response to Previous Year Reviewers' Comments

- Reviewer comment: "I don't see Plug Power in the list of collaborators. I believe they are one of the leaders in forklift sales"
  - Battelle made various efforts to include Plug Power in this effort, however they have chosen not to contribute. Alternatively Ballard provided support for MHE applications. Additionally, several collaborators have participated in the APU work.
- Reviewer comment: "We can only assume that there has been collaboration. There were no slides describing the degree of collaboration so difficult to judge. It would have been useful if the project followed the format requested"
  - A specific collaboration slide has been included to highlight collaborators and their role in the APU work.
- Reviewer comment: "Progress in the SOFC APU area has not been as good as in the MHE area."
  - Unlike MHE applications, SOFC APU systems are less technically mature and lack significant market share. FY13 work focused specifically on the SOFC APU application.

Collaborations

The following companies provided support for APU costing effort:

- NexTech Materials
  - System Design Review/Feedback
  - SOFC technology assessment
- Precision Combustion, Inc.
  - Fuel Processing Technology Review/Feedback
- Delphi
  - System Design Review/Feedback
  - BOP Design Comments
- AVL
  - System Design Review and Application feedback

Proposed Future Work

Budget Period 3	Budget Period 4
• Primary Power and CHP (PEMFC, High Temp PEMFC, SOFC) • 1 kW, 5 kW, 10 kW, 25 kW	• Large Scale Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC) • 100 kW, 250 kW

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Summary

- **Relevance:** Help answer questions on opportunities for cost reduction to penetrate non-automotive applications
- **Approach:** Perform cost modeling including DFMA® analysis of a generic fuel cell system design developed for the application
- **Technical Accomplishments and Progress:** Completed cost analysis of SOFC for APU applications. Completed cost analysis of small PEM for MHE systems
- **Technology Transfer/Collaborations:** Working with a number of industry collaborators (e.g., Delphi, NexTech Materials, PCI) for design inputs, cost inputs, design review and results review
- **Proposed Future Research:** Primary Power and CHP Applications (PEMFC, High Temp PEMFC, SOFC)