V.A.5 Cost Analyses of Fuel Cell Stack/Systems

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Objectives

The overall objective is to develop cost analyses for an 80 kW (net) direct-hydrogen polymer electrolyte membrane (PEM) fuel cell system for automotive applications. This year's (2007-2008) objectives are:

- Estimate the bottom-up manufactured cost for a 2007 PEM fuel cell stack and system configuration, assuming current technology status, and high-volume production (500,000 units/year).
- Analyze the manufactured cost of the PEM fuel cell system with today's technology at different production scales (100, 30K, 80K, 130K and 500K units/year).
- Estimate the cost of systems that meet DOE 2010 and 2015 targets.

Technical Barriers

This project addresses the following technical barriers from the Fuel Cells section (3.4.4) of the Hydrogen, Fuel Cells and Infrastructure Technologies Program Multi-Year Research, Development and Demonstration Plan:

(B) Cost

Technical Targets

This project evaluates the cost of automotive PEM fuel cell technologies being developed by DOE contractors and other developers. Insights gained from this evaluation will help guide DOE and developers toward promising materials and system-level designs and approaches that could ultimately meet the DOE targets for specific power, power density, and efficiency. DOE cost targets and current status based on the 2007 system configuration are show in Table 1.

TABLE 1. Progress Towards Meeting Cost Targets for PEM Fuel Cell Systems for Transportation Applications

Component	Units	2010 / 2015 Targets	2007 Status
Stack	$/kW$_e$	25 / 15	31
CEM[1]	$/unit	400 / 200	1080
Membrane	$/m^2	20 / 20	16
Electrocatalyst	$/kW$_e$	5 / 3	18
MEA	$/kW$_e$	10 / 5	22
Bipolar Plates	$/kW$_e$	5 / 3	3

[1]Based on 2005 cost estimate

Accomplishments

- Analyzed the manufactured cost of the PEM fuel cell stack based on 2006 technology assumptions at different production scales (100, 30K, 80K, 130K and 500K units/year).
- Completed the bottom-up costing of the 2007 stack configuration and some balance of plant (BOP) components assuming current technology status, and high-volume production (500,000 units/year).

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Introduction

The DOE seeks to develop a durable fuel cell power system for transportation applications. To ensure economic success, the fuel cell power system must be competitive in performance and cost to the internal combustion engine. A rigorous, bottom-up analysis of projected manufactured cost is required to accurately gauge the status and potential of fuel cell technology based on scenarios that meet the FreedomCAR and Fuel Partnership goals. TIAX has developed high-volume PEM fuel cell cost projections for many years, starting around 1998 for the DOE Office of Transportation

Technologies and later for the Hydrogen, Fuel Cells and Infrastructure Technologies Program.

As fuel cell vehicle technology starts to go through field demonstrations, the question of fuel cell system cost at low-volume, during early stages of commercialization, becomes pertinent. At low production volumes, material and processing costs will not benefit from manufacturing economies of scale (EOS), making the overall system much more expensive than at high production volumes. In addition, processing costs can be expected to be a much larger percentage of the manufactured cost at low-volume. Understanding the major cost contributors at low-volume can highlight nearer-term approaches and processes that might be necessary during the early stages of fuel cell vehicle commercialization.

Approach

We have applied an internally developed technology-costing methodology that uses a highly interdisciplinary approach drawing on extensive experience in the cost modeling of electrochemical and power technologies including batteries, fuel cells, and BOP components. TIAX has developed a proprietary, bottom-up, activities-based cost model in Microsoft Excel®, which is used in conjunction with the conventional Boothroyd-Dewhurst design for manufacturing (DFM) software. We have customized the cost model to accurately analyze and quantify the novel processes used (and proposed to be used) in the manufacture of PEM fuel cell stack components, while we use our experience with similar technologies for costing the BOP components.

The approach starts with a technology assessment of the system configuration and components. We perform a literature and patent search to explicate the component parts, manufacturing process, material type, internal structure and specifications. Subsequently for each component, we document the bill of materials (BOM) based on the system modeling results provided by Argonne National Laboratory (ANL), determine material costs at the assumed production volume, develop process flow charts, and identify appropriate manufacturing equipment. We also perform single-variable and multi-variable (Monte Carlo) sensitivity analyses to identify the major cost drivers and estimate the uncertainty in the results. Finally, we solicit developer and stakeholder feedback on the key performance assumptions, process parameters, and material cost assumptions; we calibrate our model using this feedback.

For the EOS analysis, we primarily used a bottom-up approach to determining the impact of production volume on the manufactured cost of each stack component. We included the impact of volume on material price, process type, equipment selection and level of automation for the major stack components. For each stack component, we then developed cost vs. volume curves over the entire range of production volumes for three scenarios: pilot plant, semi-scaled and full-scaled production. An integrated stack cost curve was compiled from these three curves comprising of the lowest cost scenario at that production volume. The production volume estimates requested by DOE were placed on this integrated curve.

Results

In 2006, we updated the performance assumptions (power density, platinum loading) and platinum (Pt) price from the 2005 cost projection. We did not change the system configuration or BOP cost projections. Overall, the 2006 assumptions lowered the stack cost by 16% to $56/kW [1,2] and the system cost by 10% to $97/kW [1,2] over the 2005 estimates [3].

We also analyzed the EOS impacts for the 2006 stack configuration. As seen in Figure 1, we found that the pilot plant scenario yields the lowest stack cost at production volumes up to 1,000 systems/year, followed by the semi-scaled scenario which yields the lowest stack cost for between 1,000 and 5,000 systems/year, finally succeeded by the full-scaled scenario which yields the lowest stack cost for any volume greater than 5,000 systems/year. As expected, the capital expenditure on manufacturing equipment controls the stack cost at low-volume, while material cost dominates as the production volume increases. It should be noted that a significant percentage of the system cost comes from Pt, which is already produced in large-volumes; consequently this contribution to cost will not benefit from EOS for material Pt price.

In addition, we worked with DOE and ANL to define the 2007 system configuration and component specifications. Figure 2 shows the PEM fuel cell system layout for 2007. Key performance assumptions

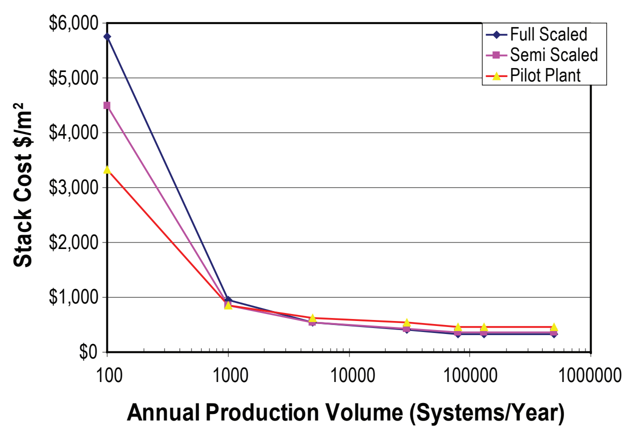

FIGURE 1. Economies of Scale for Stack Cost

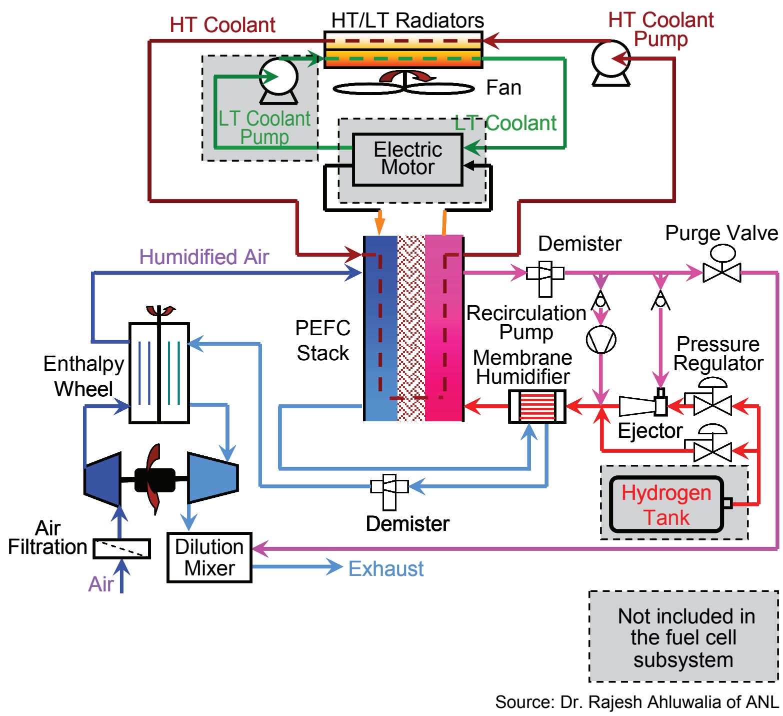

FIGURE 2. Direct-Hydrogen PEM Fuel Cell System Configuration for 2007

were updated by ANL based on data from a 3M-like stack. Table 2 lists the key stack assumptions in 2005, 2006 and 2007. These 2007 assumptions represent stack performance breakthroughs on several fronts, including a significant reduction in Pt loading with an increase in power density at higher cell voltage. The lower Pt loading and higher power density this year are attributed to the use of a nano-structured thin film catalyst (NSTFC) consisting of a ternary $PtCo_xMn_y$ alloy on an organic whisker support as opposed to Pt fines or dispersed Pt on carbon black support in previous years [4,5]. In addition to higher specific and mass activity, the NSTFC on organic whisker support is projected to have longer life due to high resistance to both support oxidation as well as Pt dissolution/agglomeration at high voltages [4,5,6]. Performance and durability demonstration in short stack tests are currently in progress [6,7].

As seen in Figure 3, the electrodes represent approximately 57% of the $31/kW fuel cell stack cost in 2007. The NSTFC material costs (primarily Pt) represent 91% of the total cost of $120/m^2 for the electrodes. In the assumed NSTFC configuration, the catalyst is coated

TABLE 2. Key Stack Assumptions in 2005, 2006 and 2007

Parameter	Unit	2005	2006	2007
Production volume	units/year	500,000	500,000	500,000
Power density	mW/cm^2	600	700	753
Cell voltage	V	0.65	0.65	0.68
Net power	kW_e	80	80	80
Gross power	kW_e	89.5	89.5	86.4
Pt cost	$/g ($/tr. oz.)	29.0 (900)	35.4 (1,100)	35.4 (1,100)
Pt conversion cost	% of Pt cost	20%	10%	10%
Pt loading (total)	mg/cm^2	0.75	0.65	0.30

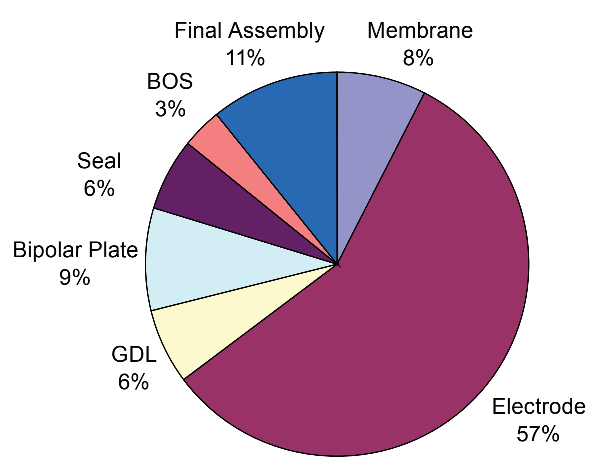

FIGURE 3. Component Contributions to Overall Stack Cost

in a thin film onto a single layer of high aspect ratio, oriented, crystalline, organic nano-whisker support [4,5,6,7,8]. The organic whisker layer is formed by vacuum sublimation (physical vapor deposition [PVD] with vacuum annealing process) of the pigment perylene red [5] (PR149). The process assumes a single step, all-dry vacuum coating process for deposition and growth of the PR149 whiskers on a microstructured substrate [4,5]. The catalyst thin film is deposited by multi-target sputtering on to the whisker support, following which the catalyst coated whiskers are transferred from the substrate to the electrolyte membrane to form a catalyst coated membrane (CCM) in a roll good process [4,5,8].

The estimated membrane cost on an active area basis is $16/m^2, with material cost representing about 87% of the total. In 2006, the membrane cost [1,2] was $23/m^2 due to higher material costs due to a thicker (50-micron) membrane and higher processing costs (double pass required for coating). This year, we have assumed a 30-micron thick, per-fluoro-sulphonic-acid (PFSA) membrane, where the ionomer has a slightly shorter side chain without the pendant –CF3 group [9], compared to a standard PFSA ionomer. The membrane includes the incorporation of functionalized additives to facilitate peroxide decomposition for better oxidative stability and enhanced water retention for higher conductivity under low humidification [7]. A membrane operating temperature of 90°C was assumed, since membrane electrode assembly (MEA) accelerated lifetime testing at 90°C and 28% relative humidity has been shown to provide good results [9].

The gas diffusion layer (GDL) cost is estimated to be $13/m^2 assuming a GDL thickness of 275 μm at 1 psi, and a woven carbon cloth cost of $14/lb. The expanded graphite foil bipolar plate cost is estimated to be $18/m^2 or $3/kW, of which material cost represents 57%. MEA and frame seal cost is estimated to be $158/m^2, of which the MEA cost is $149/m^2. We estimated a seal cost of $9/m^2 assuming Viton® ($20/lb) for the seal material as opposed to nitrile rubber ($5/lb) from previous years' analyses. Stack assembly costs of $23/m^2 represent 11% of the total stack cost of $210/m^2. Stack conditioning could be a significant cost contributor, however it was not included in this analysis.

As seen in Figure 4, BOP components represent 54% of the overall system cost of $67/kW. This estimate includes 2005 estimates for air and fuel management that will be updated later this year. The BOP includes thermal management (radiator, fan, coolant pump), water management (membrane humidifier for hydrogen and enthalpy wheel for air), air management (compressor expander motor [CEM]) and fuel management (hydrogen blower/ejectors). We estimate the price of the radiator to be $272/unit, membrane humidifier to be $160/unit and enthalpy wheel humidifier to be $250/unit.

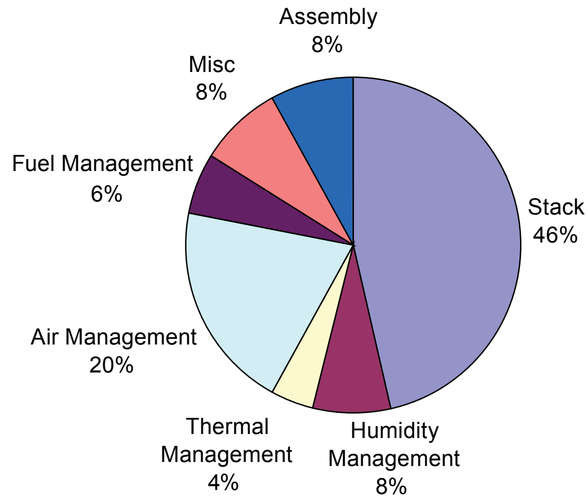

FIGURE 4. Component Contributions to Overall System Cost

Conclusions and Future Directions

- The projected 2007 stack cost of $31/kW is 45% lower than the 2006 stack cost [1,2] and 54% lower than the 2005 stack cost [3] primarily due to the progressively decreasing Pt loading and increasing power density.
- Despite lower Pt loadings, the electrodes (mostly Pt) still represent the largest contributor to stack cost (approximately 57%) in 2007.
- The estimated 2007 system cost of $67/kW is 31% lower than the 2006 system cost [1,2] and 38% lower than the 2005 system cost [3] primarily due to the decrease in the stack cost, and to a lesser degree, due to the lower bottom-up cost estimate for thermal management (~28-35% lower) and water management (~35% lower). Air and fuel management cost estimates will be updated later this year.

Our next steps are outlined below:

- Complete bottom-up manufacturing cost assessment for BOP components – air management (CEM) and fuel management (hydrogen blower/ejectors).
- Interview key developers, vendors and Fuel Cell Tech Team for feedback on performance assumptions and cost analysis; incorporate any modifications.
- Perform EOS analysis (100, 30K, 80K, 130K, and 500K units per year) for the 2007 stack and BOP components.
- Perform cost analysis of systems meeting the DOE 2010 and 2015 performance targets.
- Update performance assumptions and cost results based on on-going developer and DOE testing of state-of-the-art PEM fuel cell stacks and systems.

FY 2007 Publications/Presentations

1. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher et al., FreedomCAR Fuel Cell Tech Team presentation, Detroit, MI, April 18, 2007.

2. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher, J. Sinha, Y. Yang, S. Sriramulu, National Academy of Science Review, Washington, D.C., April 25, 2007.

3. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, S. Lasher, J. Sinha, Y. Yang, S. Sriramulu, DOE Annual Merit Review, Washington, D.C., May 18, 2007.

4. *Performance of Automotive Fuel Cell Systems for Light Duty Vehicles*, R.K. Ahluwalia et al. of ANL, S. Lasher et al. of TIAX, N. Garland et al. of DOE, IEA Annex XX Meeting, Petten, The Netherlands, May 28–29, 2007.

References

1. *Cost Analyses of Fuel Cell Stack/Systems*, Eric J. Carlson, Peter Kopf, Suresh Sriramulu, Yong Yang, DOE 2006 Hydrogen Annual Report, V.G.9.

2. *Direct Hydrogen PEMFC Manufacturing Cost Estimation for Automotive Applications*, E.J. Carlson et al., poster session at DOE Hydrogen Program Annual Merit Review, May 2006.

3. *Cost Analysis of PEM Fuel Cell Systems for Transportation*, E.J. Carlson, P. Kopf, J. Sinha, S. Sriramulu, Y. Yang, NREL Report - NREL/SR-560-39104, September 30, 2005.

4. *Nano-Structured Thin Film Ternary Catalyst Activities for Oxygen Reduction*, A.K. Schmoeckel et al., 2006 Fuel Cell Seminar, Honolulu, Hawaii, November 2006.

5. *Nano-Structured Thin Film Catalysts (NSTFC) for Next Generation PEM Fuel Cells*, Mark Debe, Northern Nano Workshop, University of Minnesota, November 2006.

6. *Durability Aspects of Nano-Structured Thin Film Catalysts for PEM Fuel Cells*, Mark K. Debe et al., ECS Transactions, 1(8) 51-66 (2006).

7. *Advanced MEAs for Enhanced Operating Conditions*, Mark Debe et al. of 3M Fuel Cell Components Program, DOE Annual Progress Report, Contract DE-FC36-02AL67621, FY 2006.

8. *Nano-Structured Thin Film Catalysts for PEM Fuel Cells by Vacuum Web Coating*, Mark Debe et al., 50th Annual Technical Conference of the Society of Vacuum Coaters, Louisville, KY, May 1, 2007.

9. *New Membranes for PEM Fuel Cells*, Steve Hamrock, 3M Fuel Cell Components Program, HTMWG meeting, St. Paul, MN, May 2005.