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Cost Analyses of Fuel Cell Stacks/Systems

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**2003 Hydrogen and Fuel
Cells Merit Review Meeting**

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TIAX LLC
Acorn Park
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Reference: D0006

In the initial tasks of the project, Argonne National Laboratory provided modeling support.

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Argonne National Laboratory
System Thermodynamic Model

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For PEMFC powertrains to be viable in the market place, they must have attractive performance and cost attributes.

Technical Targets			
System	**Efficiency**	**Cost ($/kW)**	
		2010	**2015**
Direct Hydrogen Fuel Cell Power System (including hydrogen storage)	**60%**		
Reformer-based Fuel Cell Power System • clean hydrocarbon or alcohol based fuel • 30 second start-up • satisfies emissions standards	**45%**	**45**	**30**

Barriers
N. Cost (Fuel-Flexible Fuel Processor) **O. Stack Material and Manufacturing Cost**

PEMFC powertrains are competing with mature but still evolving internal combustion engine (spark or compression ignition) technology.
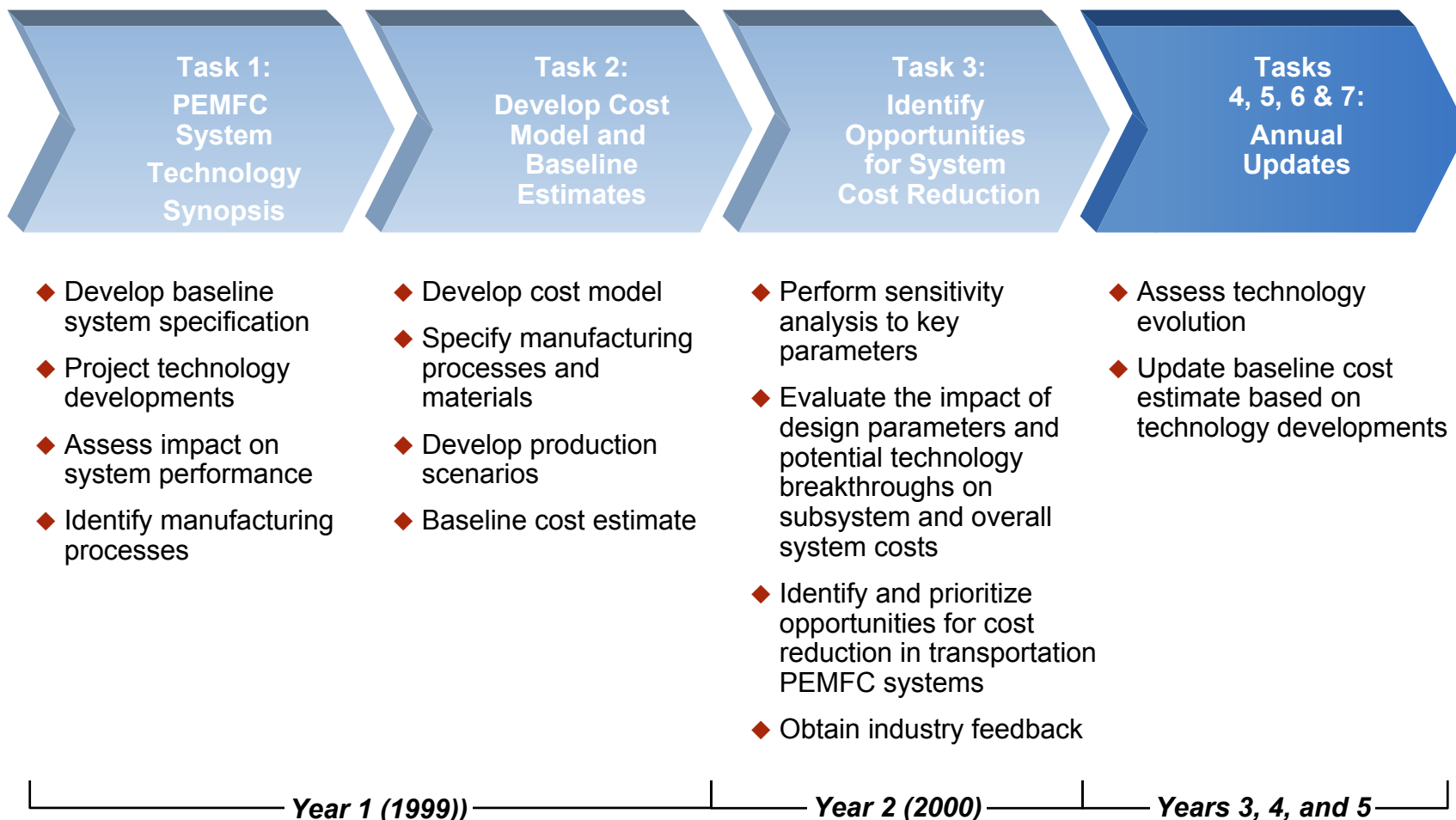
To assist DOE in the development of fuel cell system technologies by providing cost and manufacturing analysis.

- To develop an independent cost estimate of PEMFC system costs including a sensitivity analysis to:
    - Operating parameters
    - Materials of construction
    - Manufacturing processes

- To identify opportunities for system cost reduction through breakthroughs in component and manufacturing technology

- To provide annual updates to the cost estimate for the duration of the project
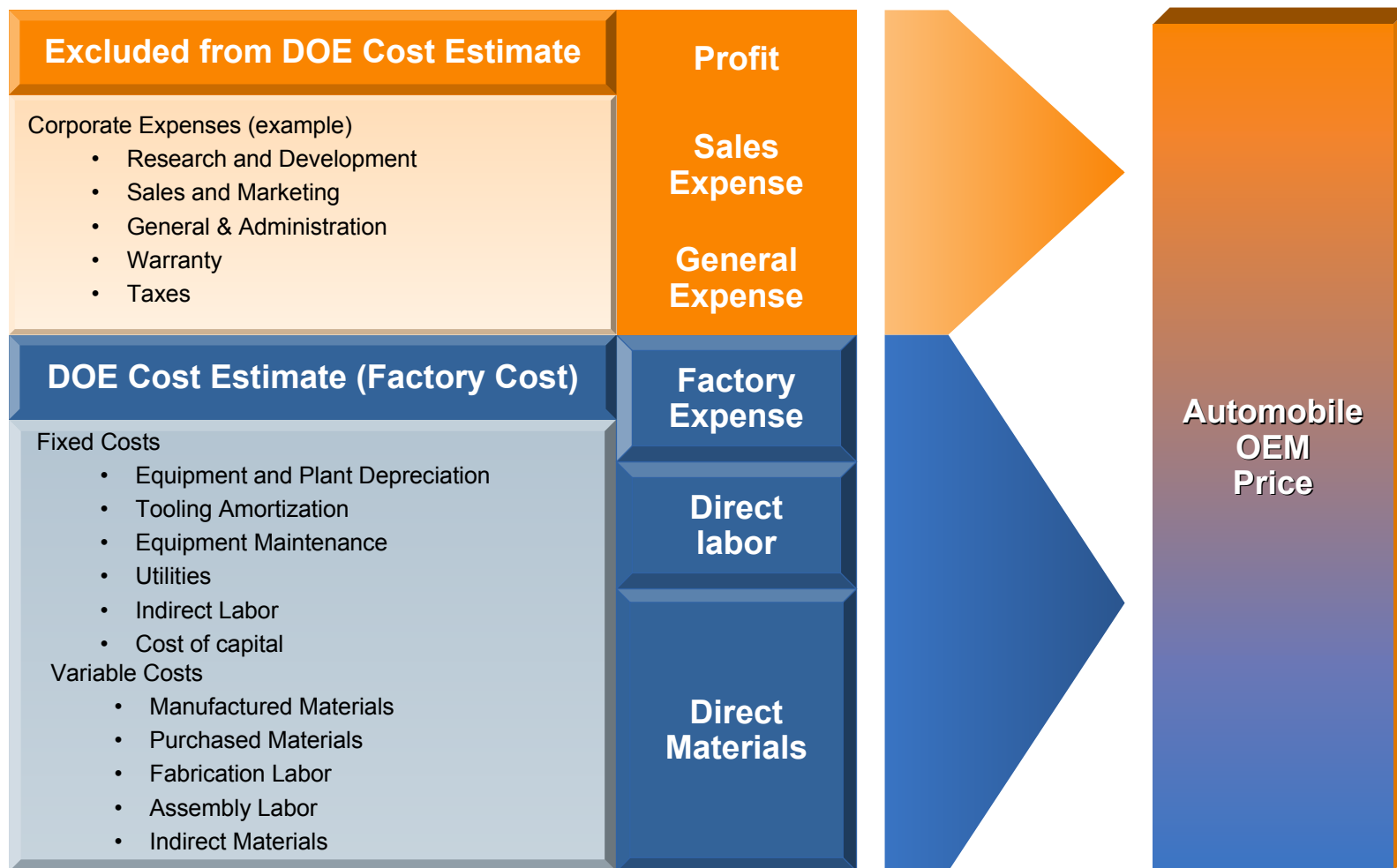
Project Approach

In this multi-year program, we developed a baseline system configuration and cost and then looked at various system scenarios and the impact of future technology developments.

Task 1: PEMFC System Technology Synopsis	Task 2: Develop Cost Model and Baseline Estimates	Task 3: Identify Opportunities for System Cost Reduction	Tasks 4, 5, 6 & 7: Annual Updates
◆ Develop baseline system specification ◆ Project technology developments ◆ Assess impact on system performance ◆ Identify manufacturing processes	◆ Develop cost model ◆ Specify manufacturing processes and materials ◆ Develop production scenarios ◆ Baseline cost estimate	◆ Perform sensitivity analysis to key parameters ◆ Evaluate the impact of design parameters and potential technology breakthroughs on subsystem and overall system costs ◆ Identify and prioritize opportunities for cost reduction in transportation PEMFC systems ◆ Obtain industry feedback	◆ Assess technology evolution ◆ Update baseline cost estimate based on technology developments

Year 1 (1999)) ——————— *Year 2 (2000)* ——————— *Years 3, 4, and 5*

Ends 3/04

Project Accomplishments

- Developed comprehensive system configuration and activities-based cost estimate for this system produced in high volume with near term available technology
  - Presented results to the fuel cell industry for feedback and incorporated this into a revised baseline cost estimate
  - Presented results to National Research Council review
  - Identified key cost drivers and development areas

- Provided program support to OATT by evaluation of system operating and future scenarios
  - High efficiency versus High Power
  - Hybrid scenarios ($/kW versus rated power)
  - Future reformer and direct hydrogen scenarios

- Program support in development of hydrogen cost targets

- Support for other DOE efforts including Full Choice Project, Report to Congress, and Annex XV

- Fundamental analysis of stack cost versus platinum loading

We have estimated the system cost up to and including factory costs for annual production volumes of 500,000.
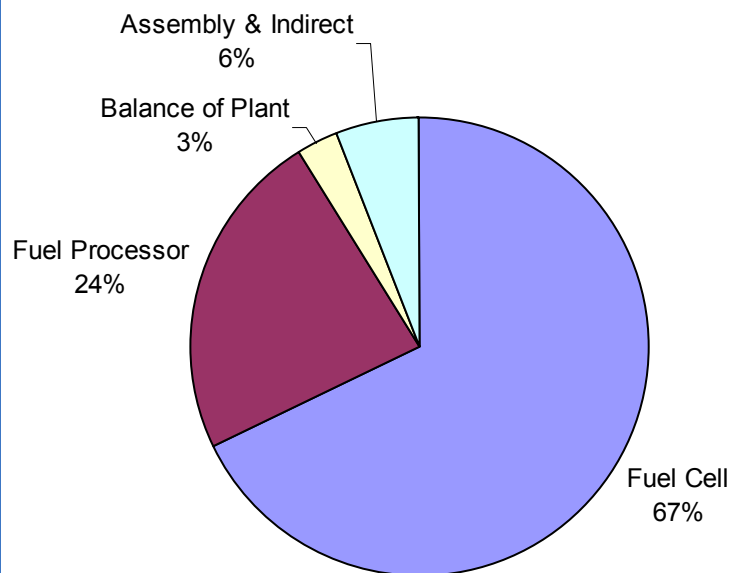
Excluded from DOE Cost Estimate

Corporate Expenses (example)
- Research and Development
- Sales and Marketing
- General & Administration
- Warranty
- Taxes

DOE Cost Estimate (Factory Cost)

Fixed Costs
- Equipment and Plant Depreciation
- Tooling Amortization
- Equipment Maintenance
- Utilities
- Indirect Labor
- Cost of capital

Variable Costs
- Manufactured Materials
- Purchased Materials
- Fabrication Labor
- Assembly Labor
- Indirect Materials

Profit

Sales Expense

General Expense

Factory Expense

Direct labor

Direct Materials

Automobile OEM Price

Individual components have been distributed between the major sub-systems as shown below.

Fuel Processor Sub-System		Fuel Cell Sub-System	Balance-of-Plant
◆ **Reformate Generator** ◆ ATR ◆ HTS ◆ Sulfur Removal ◆ LTS ◆ Steam Generator ◆ Air Preheater ◆ Steam Superheater ◆ Reformate Humidifier	◆ **Fuel Supply** ◆ Fuel Pump ◆ Fuel Vaporizer	◆ Fuel Cell Stack (Unit Cells) ◆ Stack Hardware ◆ Fuel Cell Heat Exchanger ◆ Compressor/Expander ◆ Anode Tailgas Burner ◆ Sensors & Control Valves	◆ Startup Battery ◆ System Controller ◆ System Packaging ◆ Electrical ◆ Safety
◆ **Reformate Conditioner** ◆ NH_3 Removal ◆ PROX ◆ Anode Gas Cooler ◆ Economizers (2) ◆ Anode Inlet Knockout Drum	◆ **Water Supply** ◆ Water Separators (2) ◆ Heat Exchanger ◆ Steam Drum ◆ Process Water Reservoir		
◆ Sensors & Control Valves for each section			

The fuel cell subsystem dominates the cost of the reformate system based on near-term technology but produced at high volume.

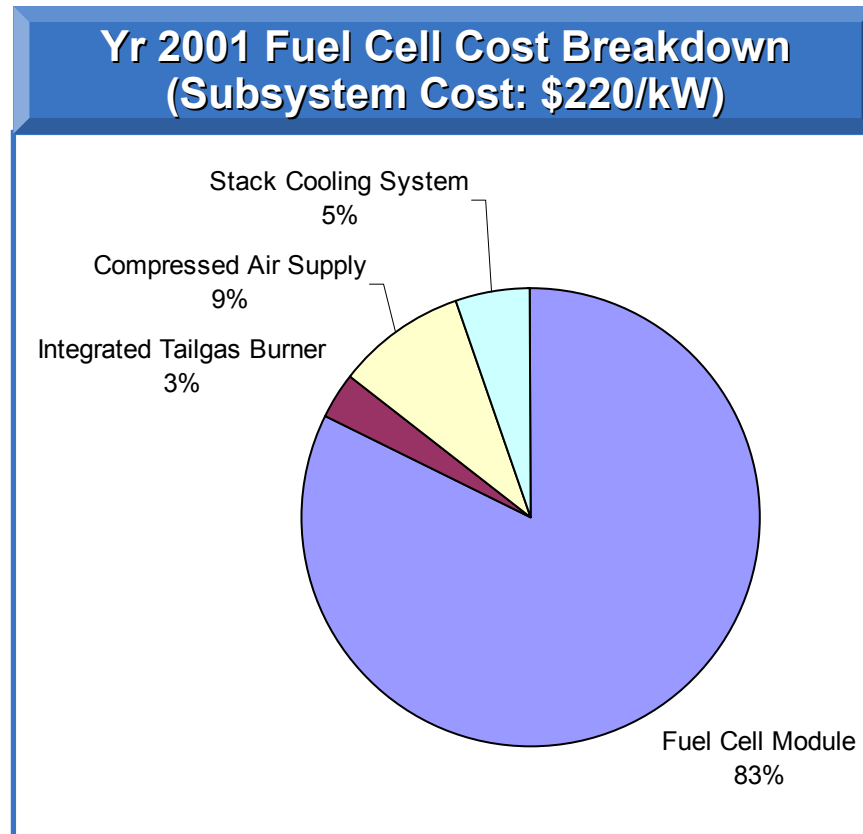

Yr 2001 Cost Breakdown by Sub-System (Total Cost: $324/kW)

Pie chart:
- Assembly & Indirect 6%
- Balance of Plant 3%
- Fuel Processor 24%
- Fuel Cell 67%

Monte Carlo Simulation of Model

Forecast: Total System Cost

10,000 Trials — Frequency Chart — 13 Outliers

Baseline System Cost
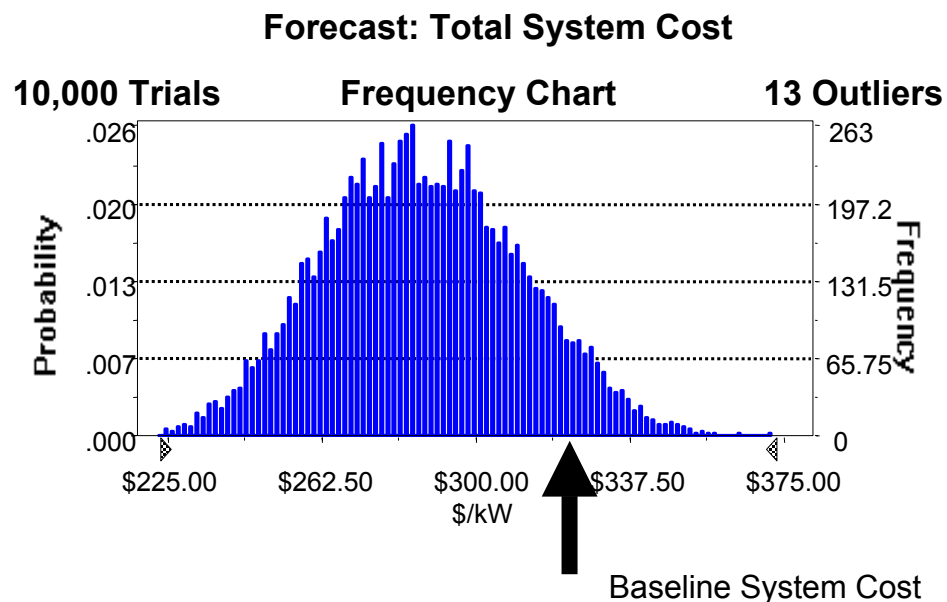
Consideration of uncertainty in the baseline model assumptions still leads to a cost over $200/kW.

The fuel cell stack dominates cost of the fuel cell subsystem, however, thermal management is critical to system size.

Yr 2001 Fuel Cell Cost Breakdown
(Subsystem Cost: $220/kW)

- Stack Cooling System 5%
- Compressed Air Supply 9%
- Integrated Tailgas Burner 3%
- Fuel Cell Module 83%

Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

Platinum and the electrolyte membrane are the major contributors to the stack cost.

Yr 2001 Fuel Cell Stack Cost Breakdown
(Stack Cost: $181/kW)

End Plates 1%
Packaging 1%
Gaskets 2%
Bipolar Interconnect 6%
Bipolar Coolant 6%
MEA 84%
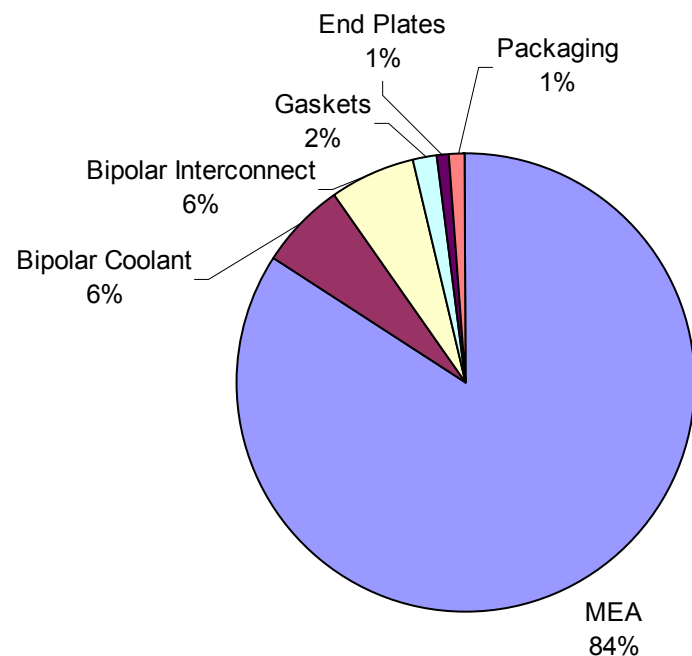
Yr 2001 MEA Cost Breakdown
(MEA Cost: $152/kW)

Gas Diffusion Layer 9%
Membrane 37%
Anode 28%
Cathode 26%

180 grams Pt (0.8 mg/cm^2) for 0.8V @ 250 mW/cm^2
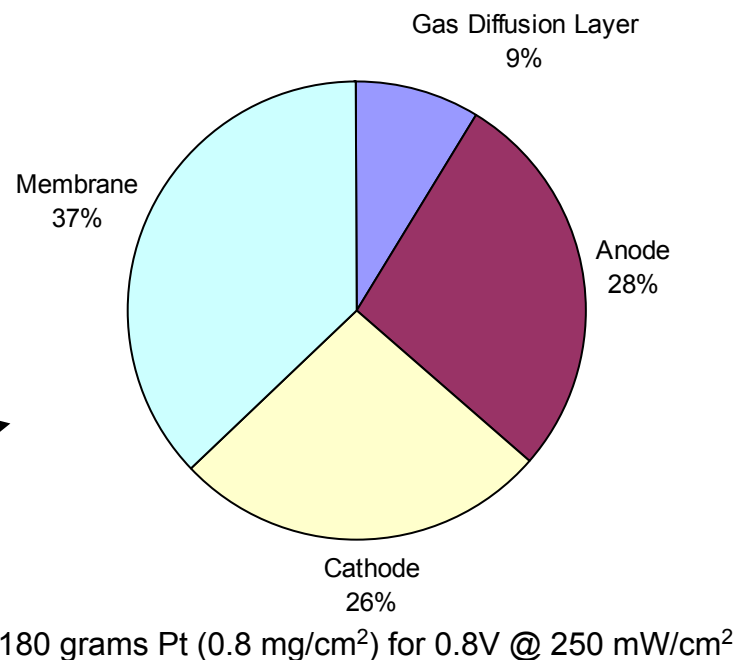
*Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

While power density determines the actual amount of material in the system. Parasitic power losses further increase size and cost.

System simplification and cost reduction of components will be needed to reduce the cost of non-catalytic materials and components.

Yr 2001 Fuel Processor Cost Breakdown (Cost: $76/kW)

Fuel Supply
3%

Fuel Processor
Water Supply
28%

Reformate
Generator
46%

Reformate
Conditioner
23%
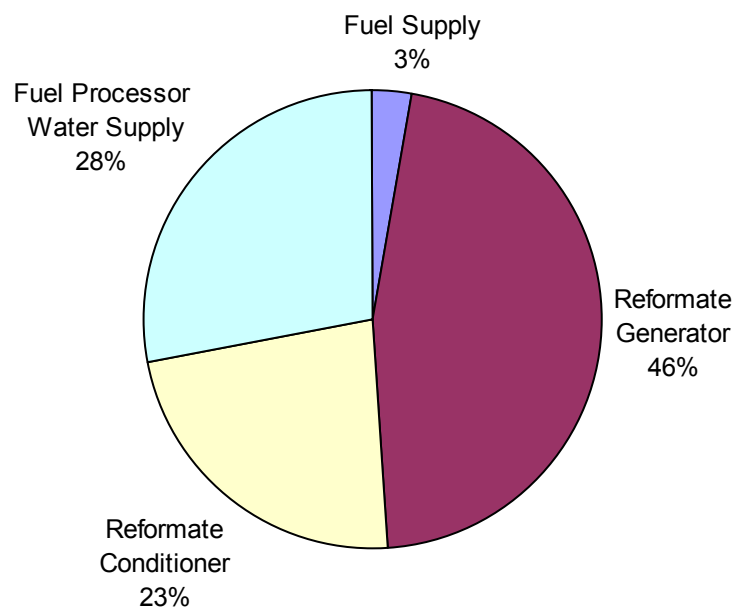
Yr 2001 Fuel Processor Cost Breakdown by Material

Other
2%

ATR Bed
15%

Stainless
18%

PROX Bed
8%

2 Pumps/ 1 Motor
5%

HTS Bed
4%

LTS Bed
9%

10 Valves
15%

ZnO Bed
1%

15 Sensors
17%

7 Heat Exchangers
6%
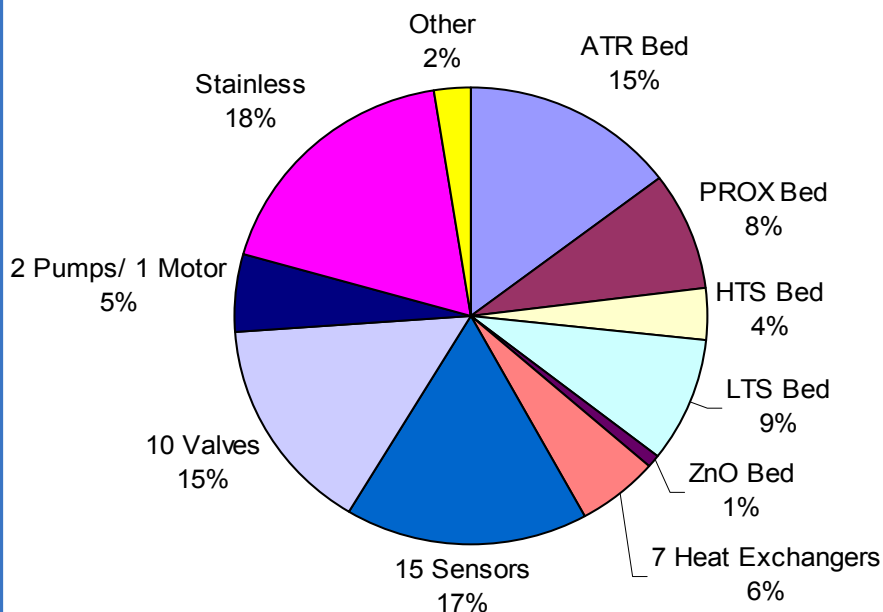
*Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

Some of the cost benefits of reducing total rated power in a hybrid system will be offset by increased cost per kW arising from fixed costs.
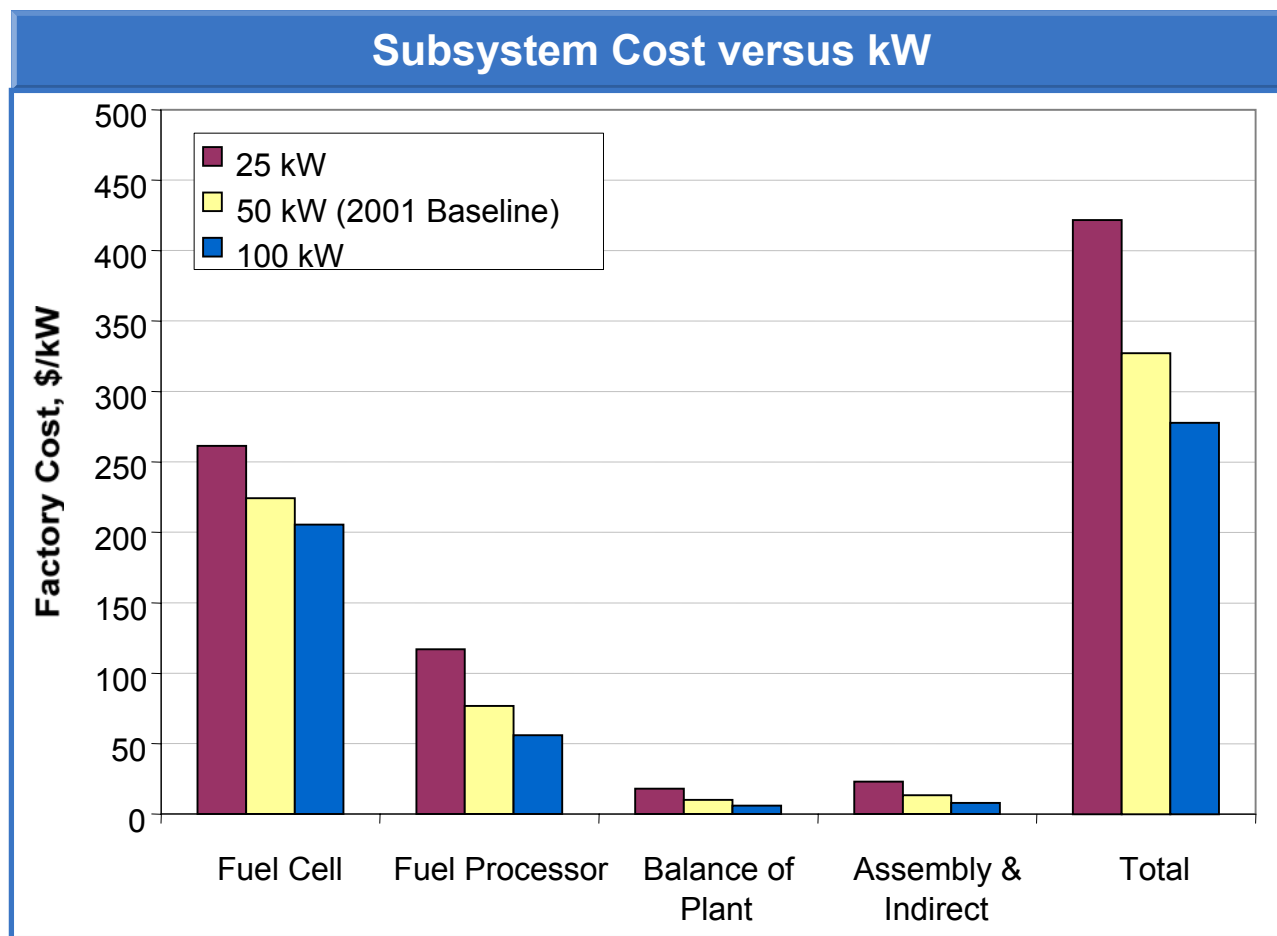
Basis: 50 kWe net, 500,000 units/yr. Not complete without assumptions.

The potential for reduction in platinum loading was estimated by calculating 'best-case' cathode polarization curves for various operating conditions.

$$V^{cell} = V^{OC} - J\,R_{total} - \eta_c - \eta_a$$

Baseline experimental activity data (h_c Vs. i)	**Correct data for :**	**Account for:**	**h_c Vs. J for any T, P, Loading**
• 60 C • 1 atm O_2 • Aqueous electrolyte • 3.5 nm Pt	Temperature (T) Partial pressure (P_{O2}) • Solubility of O_2 in the electrolyte • Alloy catalyst activity	Loading • Area utilization • Particle size effects	
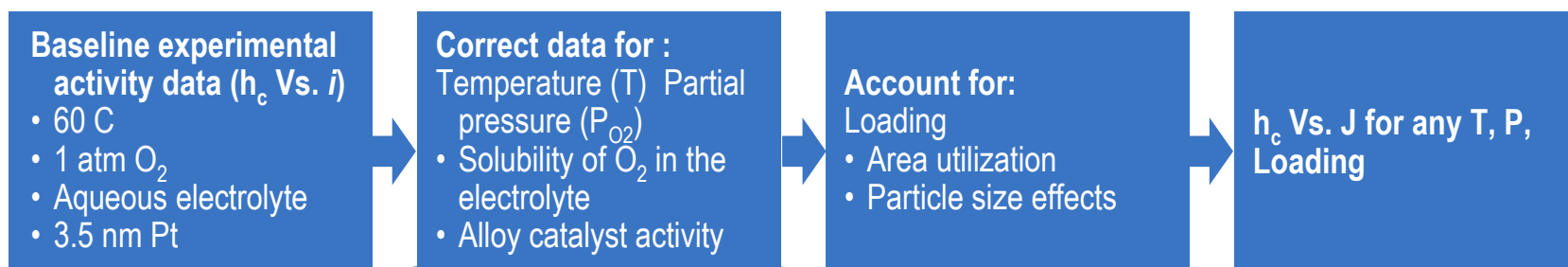
Tafel Kinetics	Parameter	Value
$$i = \gamma i_0 \exp\left[\dfrac{\eta}{b}\right]$$ $$i_0 = k\left(sP_{O_2}\right)^n \exp\left[-\dfrac{E_a}{RT}\right]$$	i_0 - Exchange current density b - Tafel Slope k - pre-exponential factor n - Reaction order s - O_2 solubility E_a - Activation energy	Experimental data[1] Experimental data[1] 2 x Pt activity (Pt:Ni)[2] 1 (Exp. data)[1] 3 x that in water (Exp.)[3] 28 kJ/mol (Exp.)[1]

[1] U. Paulus, T. J. Schmidt, H. A. Gasteiger, R. J. Behm, J. Electroanal. Chem., 495 (2000) 134.
[2] P. N. Ross, N., Markovic, T. J. Schmidt, V. Stamenkovic, in DOE 2001 Review, OTT Fuel Cells program, ORNL (2001)
[3] S. Gottesfeld and T. Zawodzinski in R. C Alkire, H. Gerischer, D. M. Kolb, C. W. Tobias (Eds.), Adv. Electrochem. Sci. Eng. V 5, Wiley-VCH, Weinhem (1997).

A minimum platinum loading of 0.2 - 0.4 mg/cm2 is needed to achieve DOE power density goals (0.4 A/cm^2 @ 0.8 V) at 120 C.
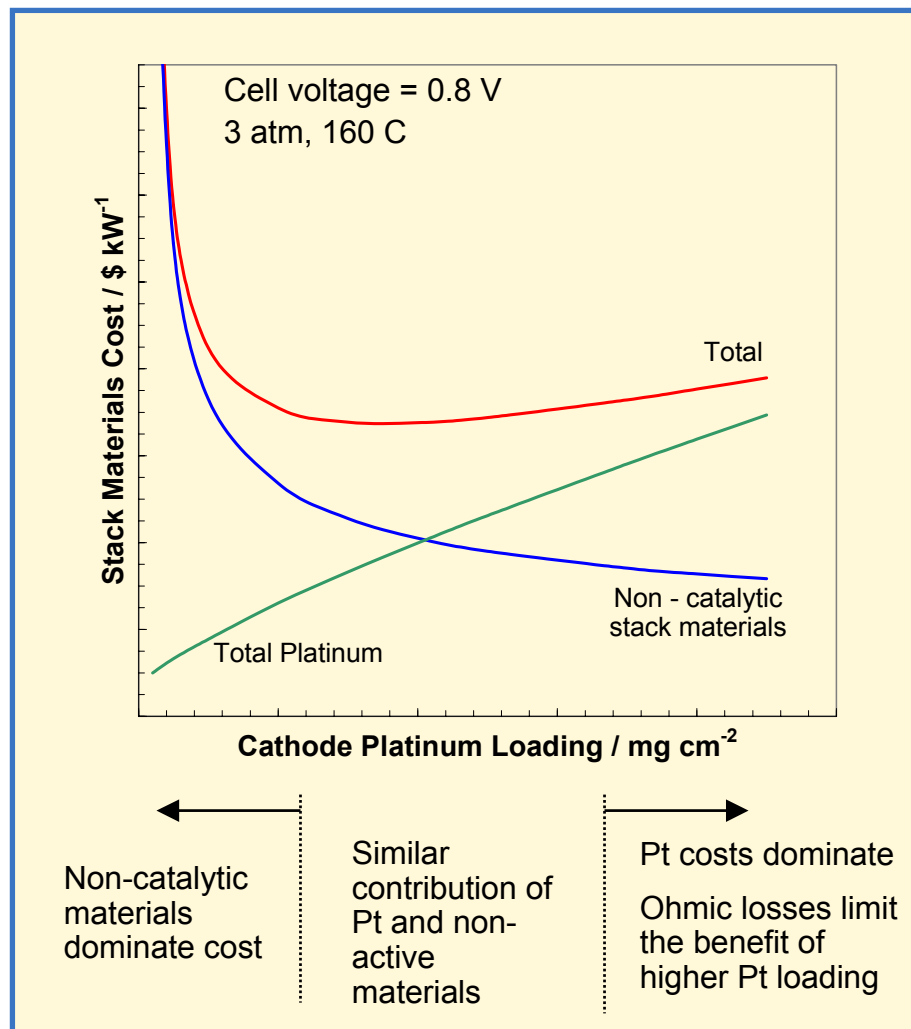
Operating Conditions:
3 atm, 2x Pt activity, R_t = 0.1 Ω cm^{-2}, 3.5 nm catalyst diameter
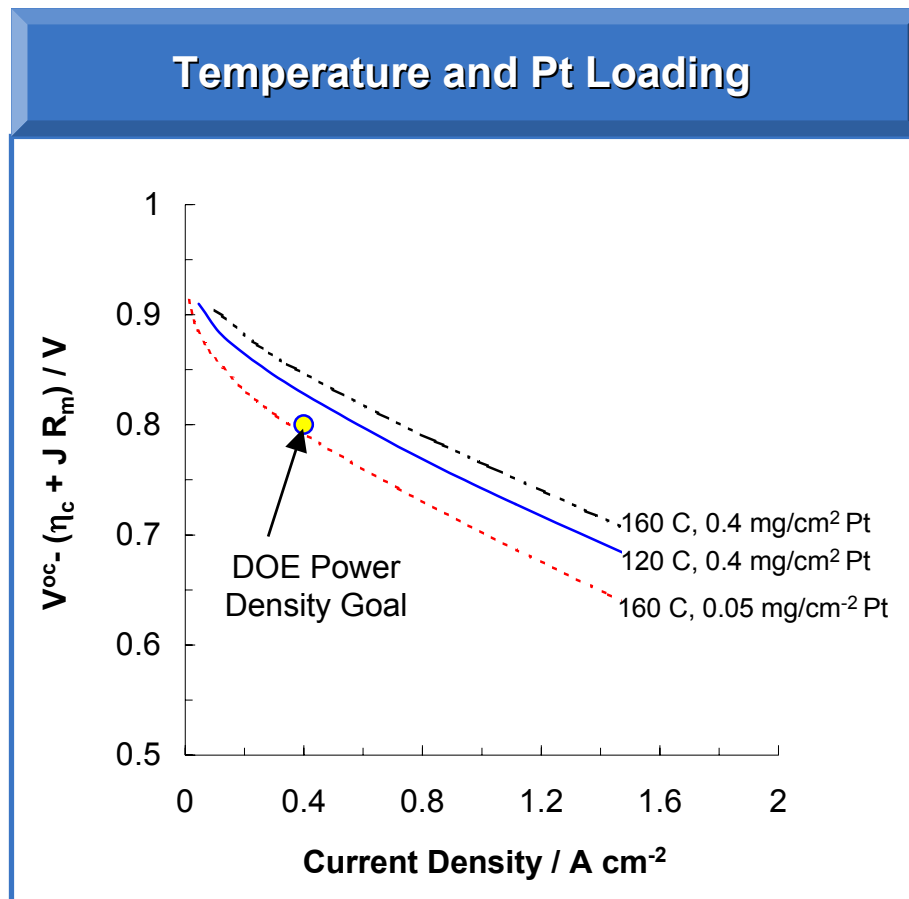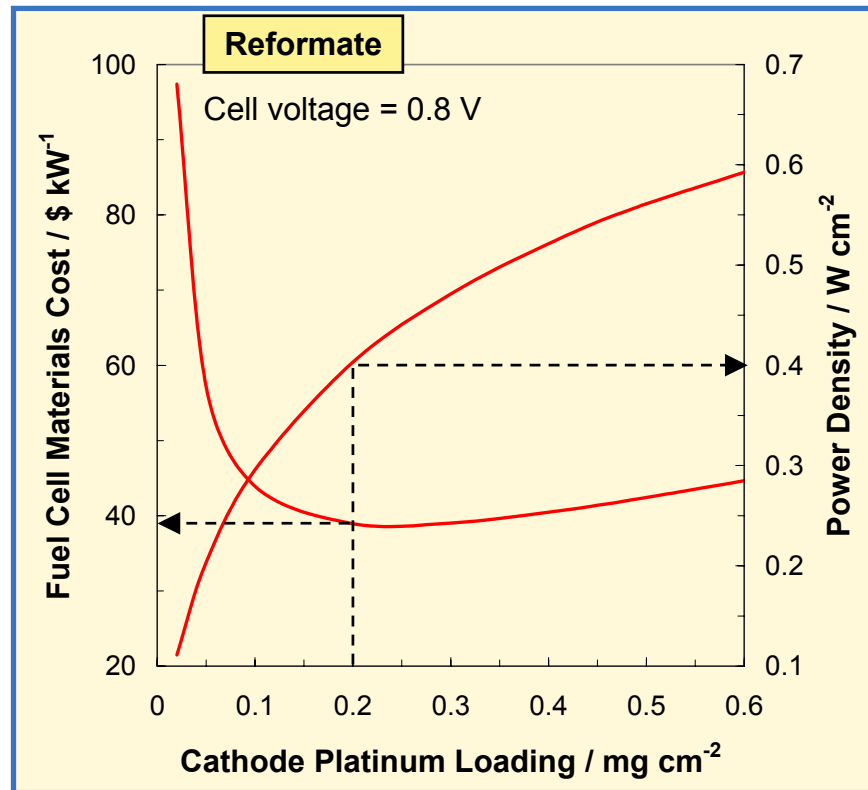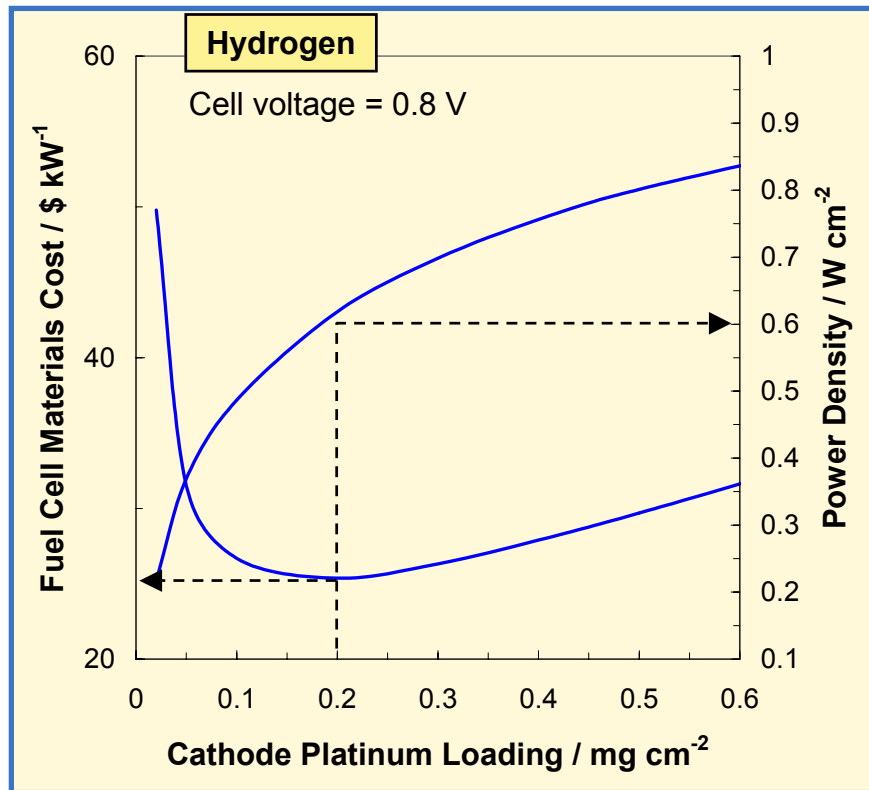

Voltage losses at the anode will lower the estimated curves.

Increasing stack costs due to non-catalytic materials limits the benefit of reducing platinum loading below a certain value.

In both reformate and direct hydrogen cases, the minimum in stack material costs occurs around cathode platinum loadings of 0.2 mg/cm².

Assumptions	Hydrogen	Reformate
Anode overpotential (mV)	0	30
Membrane Resistance (mΩ cm²)	50	50
Electronic Reisistance (mΩ cm²)	20	20

Operating Conditions:
0.8 V, 3 atm, 160 C, 3.5 nm Particles, 2x Pt activity

The cell resistance (ionic + electronic) has a significant influence on the cost-effectiveness of platinum usage in the stack.
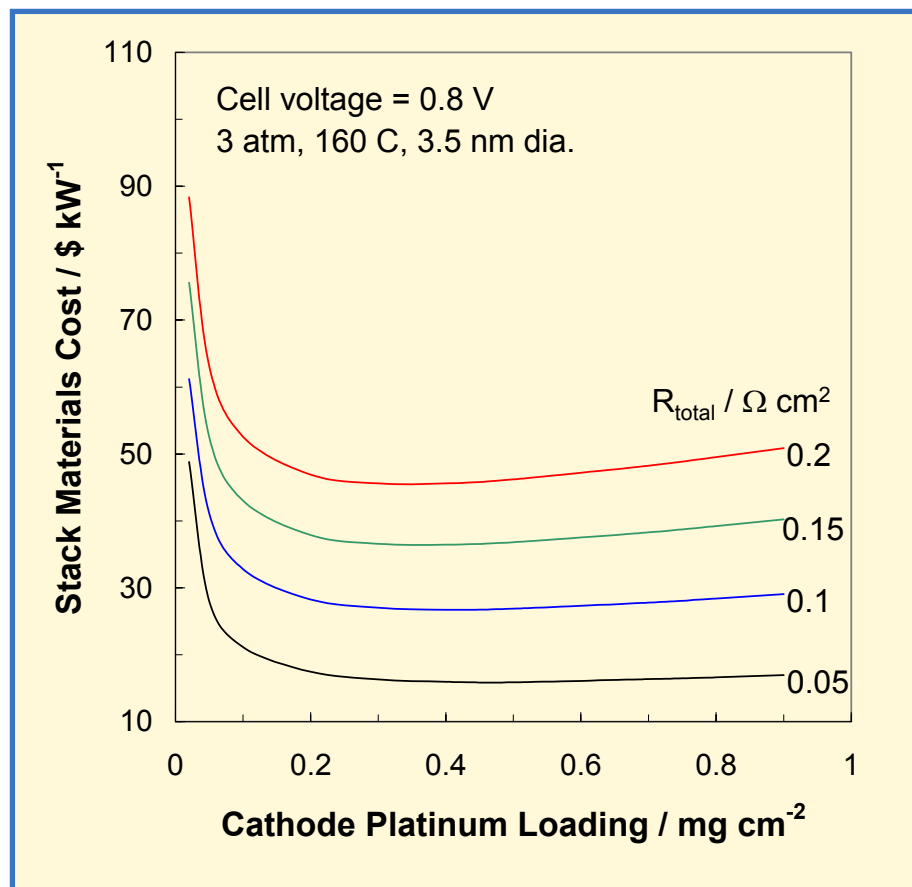
Assumptions: Anode Pt loading = 50 % of that of the cathode, Platinum cost = 18,000 $/kg, Membrane cost = 50 $/m^2, Bipolar + coolant plate = 22 $/m^2, GDL = 31 $/m^2
Operating Conditions: 0.8 V, 3 atm, 160 C, 3.5 nm Particles, 2x Pt activity

The platinum content for the DOE Goals scenario is much lower than the other cases due to its very aggressive cathode loading assumption.

MEA Precious Metal Calculation	Current Reformate	Future Reformate	Future Hydrogen	DOE Goals Reformate
Cathode Pt Loading, mg/cm^2	0.4	0.2	0.2	0.05
Anode Pt Loading, mg/cm^2	0.4	0.1	0.1	0.025
Power Density, mW/cm^2	248	400	600	320
Gross System Power, kW	56	53	53	56
Cathode Pt, g	90	26	18	8.8
Anode Pt, g	90	13	8.8	4.4
Anode Ru, g	45	6.6	0	2.2
Stack Precious Metals, g	**225**	**46**	**27**	**15**

Projection of future system costs were made by assuming higher power densities, advances in reformer technology, and compressed hydrogen storage.

Parameter	Baseline	Future Reformate	Future Hydrogen
Stack Improvements			
◆ Current Density (mA/cm^2)	310	500	760
◆ Power Density (mW/cm^2)	250	400	610
◆ Cathode Pt (mg/cm^2)	0.4	0.2	0.2
◆ Anode Pt (mg/cm^2)	0.4	0.2	0.1
◆ Anode Ru (mg/cm^2)	0.2	0.0	0.0
Fuel Processor Improvements		◆ Short contact time reactor ◆ Improved shift catalysts ◆ No sulfur bed ◆ No PrOX	◆ No Fuel Processor ◆ Compressed H$_2$ storage ◆ Simpler tailgas burner
System and Material Cost Reduction		Reduced Sensor, CEM, and Membrane costs	

One can project significant cost reductions due to advances in technology, however, further improvements are required to achieve DOE goals.
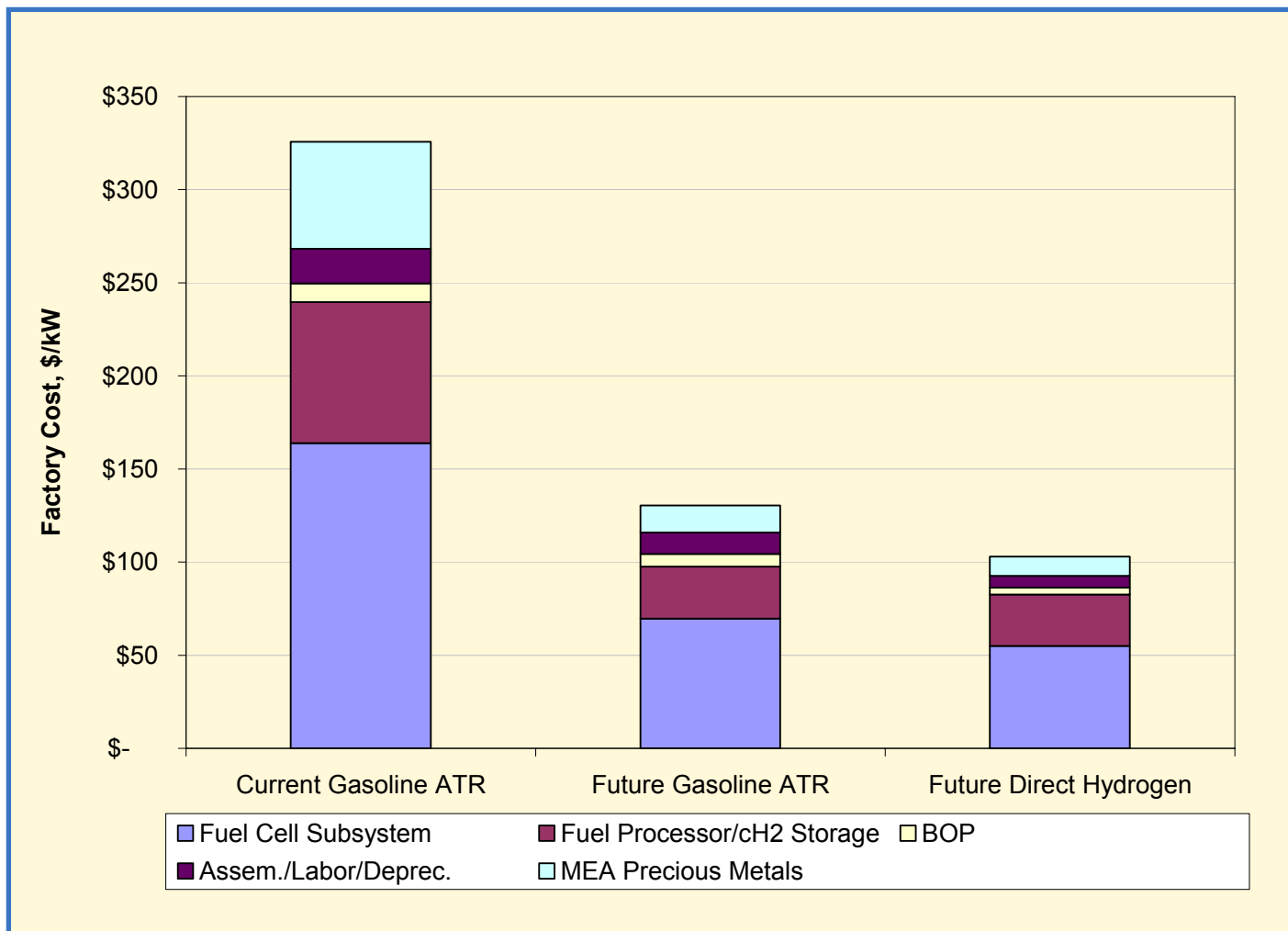
Next Steps

- Provide 2003/2004 Cost Update

- Provide program support as required