Cost Analysis of Fuel Cell System for Transportation

Baseline System Cost Estimate

Task 1 and 2 Final Report to:
Department of Energy:

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Topic 1 Subtopic 1C

The following report summarizes the results of a DOE funded assessment of the cost of a 50 kW fuel cell system for transportation including a multi-fuel capable reformer, a PEM fuel cell, and balance-of-plant components.

The results of the model should only be considered in conjunction with the assumptions used in selecting and scaling the system components. The components have been scaled using technology assumed available in Year 2000 and costed assuming production volumes of 500,000 vehicles.

In developing the system configuration and component manifest we have tried to capture all of the essential engineering components and important cost contributors. However, the system selected for costing does not claim to solve all of the technical challenges facing fuel cell transportation systems or satisfy PNGV fuel cell vehicle performance targets.

The system specifications and cost projections presented in this report will be updated during the Year 2000 based on discussions with the general fuel cell development community.

Our program was supported by the system modeling group within Argonne National Laboratory.

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Our program was supported by the system modeling group within Argonne National Laboratory.

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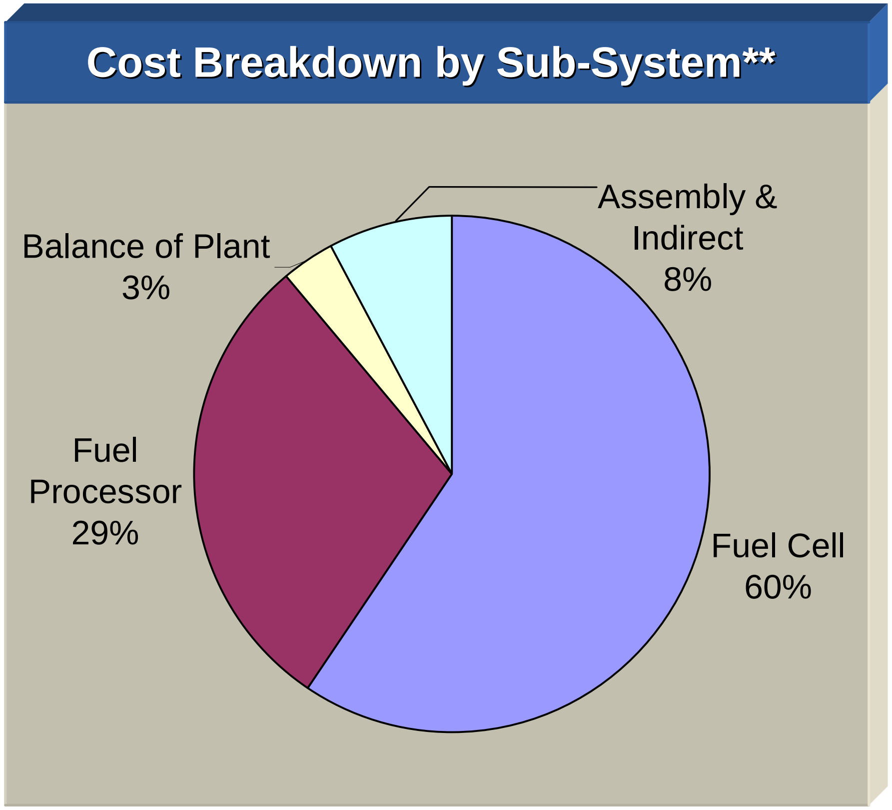
The Year 2000 baseline fuel cell and fuel processor system cost estimate is at least $300/kW.

Sub-System	Factory Cost			
	Yr 2000 Estimate*		PNGV Goals($/kW)	
	($)	($/kW)	Yr 2000	Yr 2004
Fuel Cell	8,850	177	100	40
Fuel Processor	4,310	86	30	10
BOP	500	10	Not listed separately in PNGV Goals	
System Assembly	1,040	21		
Total	**14,700**	**294**	130	50



Basis: 50 kWe net, 500,000 units/yr ** Sub-system components described in body of the report

The system components were scaled by estimated performance available in Year 2000, but cost modeled as if in production at high volume.

The power density of the individual sub-systems must be increased significantly for the system to meet PNGV performance targets.

		Specific Power Year 2000 (W/kg)	
Sub-System	**Weight (kg)**	**Baseline System Estimate**	**PNGV Target**
Fuel Cell	295	169	350
Fuel Processor	215	233	600
Total*	**620**	**80**	**250**

Basis: 50 kWe net; * Total includes 110 kg for Balance-of-Plant components

For reference, the fuel cell stack alone has a specific power of 315 W/kg (56 kW_e/179 kg). Specification of fuel cell operation at high efficiency (e.g. 0.8 volts) approximately doubles the size and cost of the fuel cell.

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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
  - Fuel type
  - 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 four (4) years as technology evolves

In the 1999 year program we completed Tasks 1 and 2. This report summarizes our findings and results for these tasks.

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 design parameters and manufacturing processes ◆ Perform risk analysis to key parameters	◆ Assess technology evolution ◆ Revise Year 1 cost estimates based on technology developments and revised projections
Year 1 (1999–2000)			***Years 2, 3, 4, and 5***

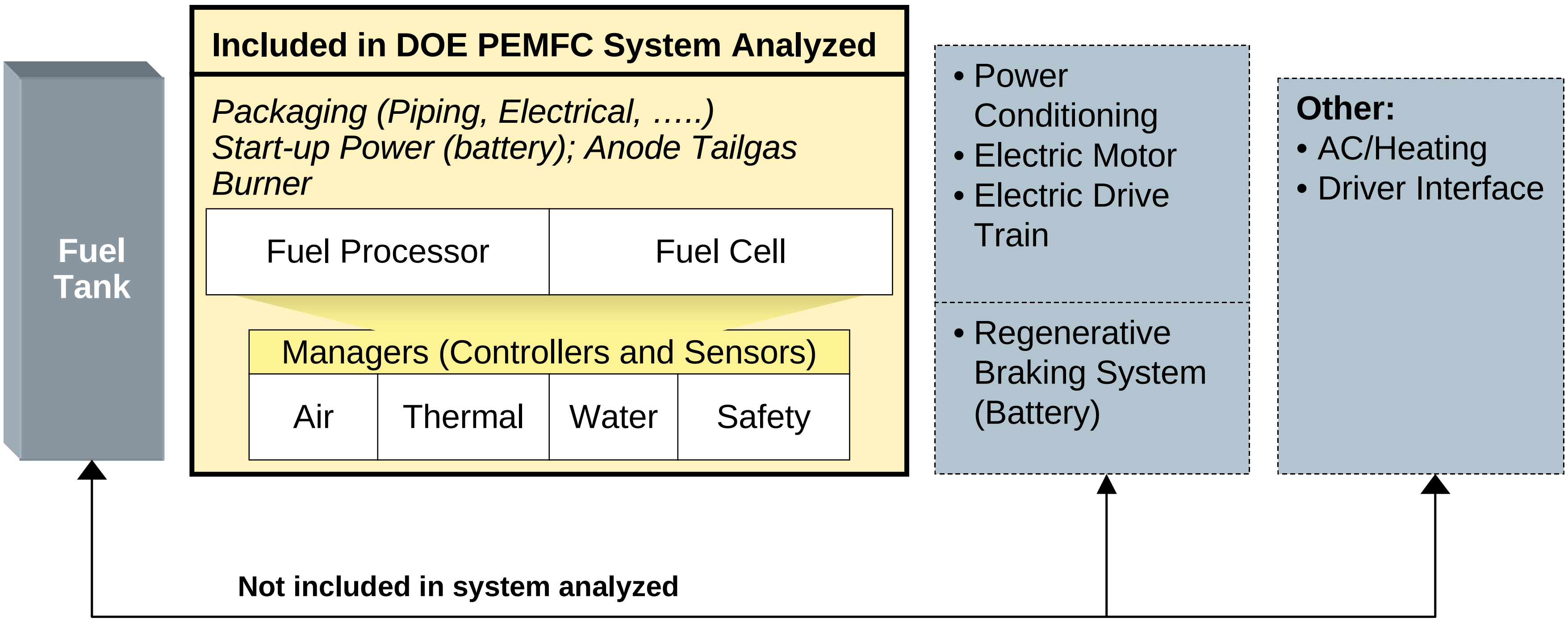
The PEMFC cost model results reported here were developed based on the critical assumptions listed below.

- Fuel processor, fuel cell stack, and directly related balance-of-plant components are included in the estimated factory cost of the PEMFC system
  - Factory cost includes fixed and variable costs but excludes corporate charges (e.g. profit, sales and general expenses)
- Based on Year 2000 available technology
  - High efficiency commensurate with PNGV goals (e.g. 35-40%)
  - Water self-sufficiency
  - Fuel flexible (designed for gasoline)
  - Autothermal Reformer (ATR)
  - Turbocompressor (e.g. Allied Signal)
- Based on high production volumes (500,000 vehicles per year)

The following additional issues should also be kept in mind as we discuss the Year 2000 baseline system technology and cost.

- Several balance-of-plant (BOP) components included in the system have not figured significantly in earlier cost models of PEMFC systems
  - The anode tailgas burner plays several key roles (startup, energy recovery, and emissions control)
  - Controls and sensors based on current technology and costing contribute significantly to the BOP
  - Batteries for parasitic power drains during startup (e.g. compressor and pumps) for approximately “10 minutes” have not been considered
  - Assumption of 95^{o}F ambient temperature does not consider operation in warmer climates and potentially underestimates heat exchanger size
- Fuel processor catalyst materials are an area of active research and development
  - Performance, cost, and robustness assumptions of these catalysts are critical to scaling and costing the fuel processor

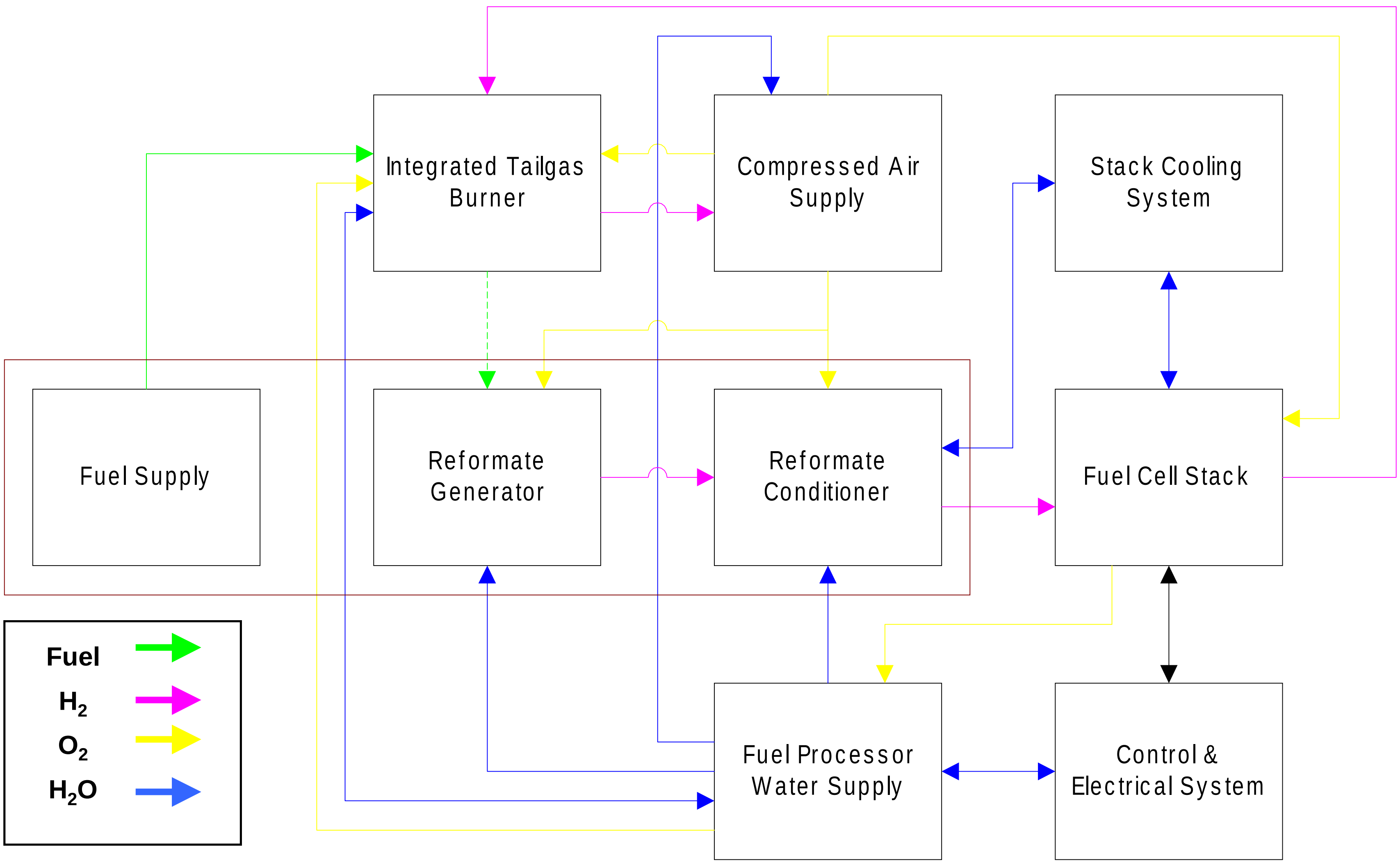
A fuel cell vehicle would contain the PEMFC system modeled in this project along with additional electric drive train components.



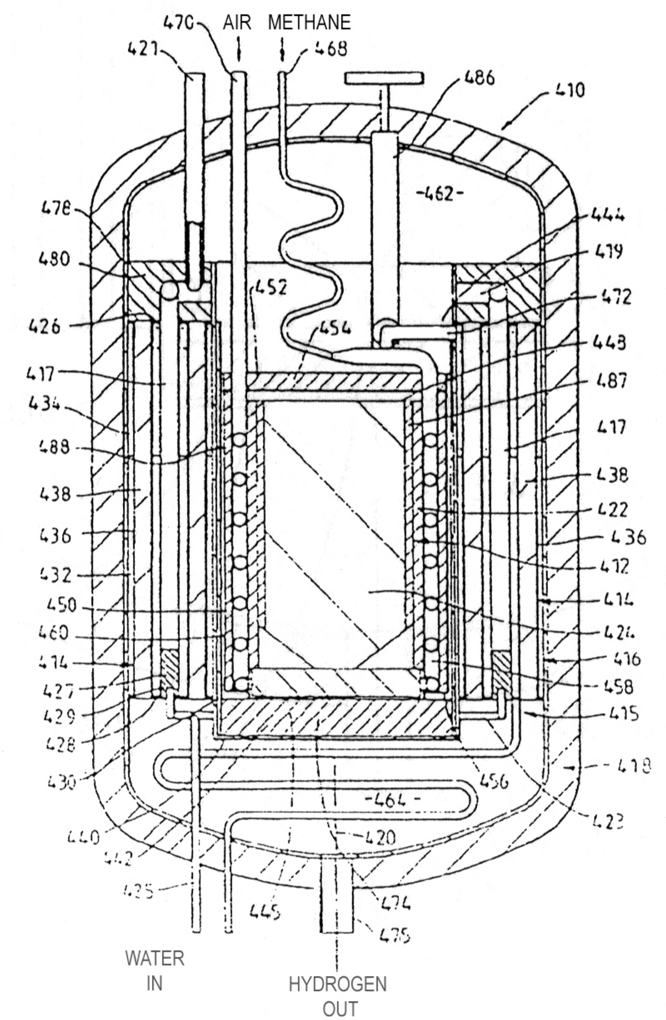
Individual components have been distributed between the major sub-systems as shown below for the Year 2000 baseline system.

<table>
<tr><th colspan="2">Fuel Processor Sub-System</th><th>Fuel Cell Sub-System</th><th>Balance-of-Plant</th></tr>
<tr><td>◆ Reformate Generator
◆ ATR
◆ HTS
◆ Sulfur Removal
◆ LTS
◆ Steam Generator
◆ Air Preheater
◆ Steam Superheater
◆ Reformate Humidifier</td><td>◆ Fuel Supply
◆ Fuel Pump
◆ Fuel Vaporizer</td><td rowspan="3">◆ Fuel Cell Stack (Unit Cells)
◆ Stack Hardware
◆ Fuel Cell Heat Exchanger
◆ Compressor/Expander
◆ Anode Tailgas Burner
◆ Sensors & Control Valves</td><td rowspan="3">◆ Startup Battery
◆ System Controller
◆ System Packaging
◆ Electrical
◆ Safety</td></tr>
<tr><td>◆ Reformate Conditioner
◆ NH_3 Removal
◆ PROX
◆ Anode Gas Cooler
◆ Economizers (2)
◆ Anode Inlet Knockout Drum</td><td>◆ Water Supply
◆ Water Separators (2)
◆ Heat Exchanger
◆ Steam Drum
◆ Process Water Reservoir</td></tr>
<tr><td colspan="2">◆ Sensors & Control Valves for each section</td></tr>
</table>

The major components and sub-systems of the baseline system are shown below:



We used an integral reformate generator/shift reactor containing a: CATR, air preheater, superheater, humidifier, HTS, ZnO sulfur removal bed, steam generator, and LTS. The general design is similar to that shown in a Rolls Royce patent.



Catalyst space velocities were based on catalyst activities published by Argonne National Laboratory.

The design parameters for the fuel processor were chosen to achieve high cold gas efficiency.

	Catalyst Beds				Clean-up Beds	
Parameter	ATR	HTS	LTS	PROX	Sulfur Removal	NH_3 Removal
Temperature C	1030	430	230	205	490	80
Catalyst	Pt/Ni	Fe_3O_4/ CrO_3	Cu/ZnO	Pt	ZnO	Activated Carbon
Support	Alumina	Alumina	Alumina	Alumina	None	None
GSHV (1/hour)	15,000	10,000	5,000	10,000	NA	None
Bed Volume (L)	10.3	13.3	26.5	13.3	2.8	5.5
Bed Weight (kg)	13	17	37	15	8	3

Phi = 2.9; Steam/Carbon Ratios: ATR - 2.2, System Total - 3.5

The catalyst activities are based on suggested values from ANL/DOE.

A high unit cell voltage rather than a high power operating point on the fuel cell polarization curve was selected to satisfy overall system efficiency goals.

Operating Conditions	Units	Baseline Assumptions
Unit Cell Voltage	volts	0.8
Current Density	mA/cm^2	310
Power Density *	mW/cm^2	250
Temperature	^oC	80
Percent anode air bleed	%	1
Anode Stoichiometry		1.2
Cathode Stoichiometry		2.0
Fuel Utilization	%	85
H_2 Concentration (dry basis)	%	40

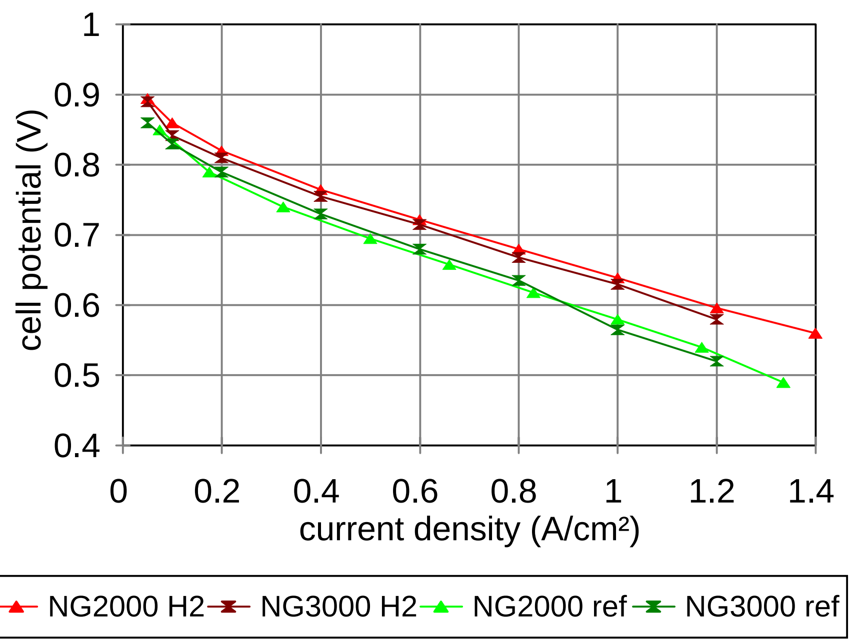
Stack Parameter	Value
Fuel Cell Module Voltage (volts)	300
Net Power (kW)	50
Net System Parasitic Power (kW)	6
Number of Stacks in Series	2
Current (Amperes)	186
Active Area (cm^2)	600
Unit Cells per Stack	188
Cooling Plates per Cell	1

*Combined anode and cathode Pt loading: 0.8 mg/cm^2 ; Ru loading on anode: 0.2 mg/cm^2

This is a major departure from current practice, and is being reexamined by Arthur D. Little and other DOE contractors.

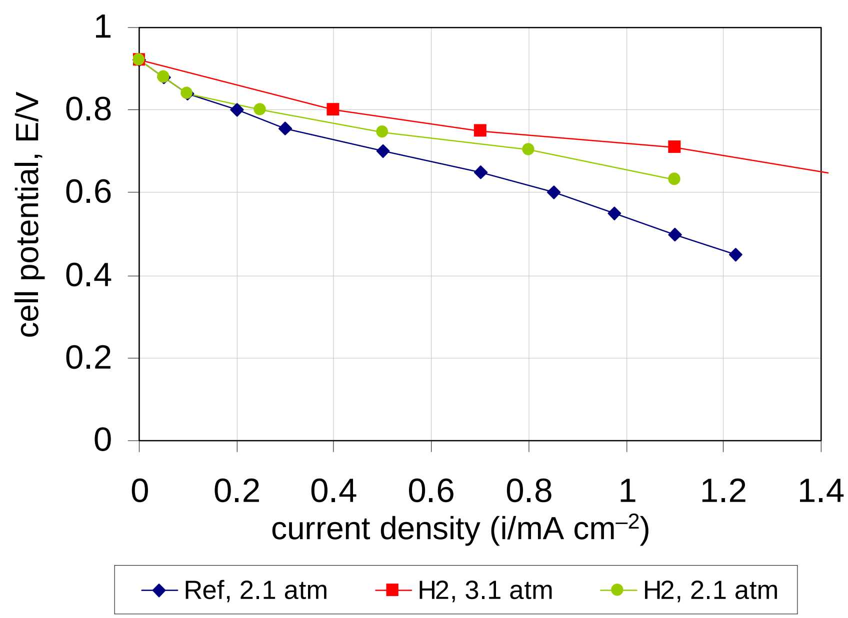
A current density of 300 mA/cm² at 0.8 volts was selected on the basis of near term projections of available stack and unit cell data.

Stack Data



Stack data from Energy Partners, Inc. NG2000 was a stack of 600 cm2 active area, NG 2000 - 292 cm^2 active area, NG 3000 - 596 cm^2 active area. Reformate composition was 40 % H_2, 40 % N_2, 20 % CO_2. H_2/air = 1.2/2 Stoichiometry.

Single Cell Data



Single cell data from W. L. Gore and Associates employing the PRIMEA@ MEAS. Cell area area was 25 cm^2. Reformate composition was 100 ppm CO, 100 ppm CH_4, 48 % H_2, 31 % N_2, 21 % CO_2. H_2/air = 1.5/2 Stoichiometry, pressure = 2.1 atm, temperature = 77 ^{0}C.

Source: B. Bahar, C. Cavalca, S. Cleghorn, J. Kolde, D. Lane, M. Murthy, and G. Rusch, *J. New Mat. Elect. Sys.*, 2 (1999) 179

The PNGV system description does not account for the complexity of many of the components within the system.

Component	Description
Integrated Tailgas Burner	3 reaction zones
Compressed Air Supply	Compressor/expander, cathode humidifier,air filter, valves
Fuel Processor Water Supply	2 water separators, cathode condenser, process water radiator, process water pump, steam drum, filters, valves, sensors
Stack Cooling System	Stack radiator, stack cooling water pump, valve, sensors
Startup Power	Batteries, switching regulator
Controls & Electrical System	Main control board, main wire harness, power wiring, contactor (safety)

The power density of the individual sub-systems must be increased significantly for the system to meet PNGV performance targets.

		Specific Power Year 2000 (W/kg)	
Sub-System	Weight (kg)	Baseline System Estimate	PNGV Target
Fuel Cell	295	169	350
Fuel Processor	215	233	600
Total*	**620**	**80**	**250**

Basis: 50 kWe net; * Total includes 110 kg for BOP

For reference, the fuel cell stack alone has a specific power of 315 W/kg (56 kW$_e$/179 kg). Operation of the fuel cell at high efficiency (high voltage) approximately doubles the size of the fuel cell.

Per DOE’s direction, we have estimated the system cost up to and including factory costs.

Excluded from DOE Cost Estimate

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

Profit

Sales Expense

General Expense

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

Factory Expense

Direct labor

Direct Materials

Automobile OEM Price

We have assumed manufacturing and purchased part decisions are consistent with current OEM or major vehicle integrator practices and production volumes equal to 500,000 units per year.

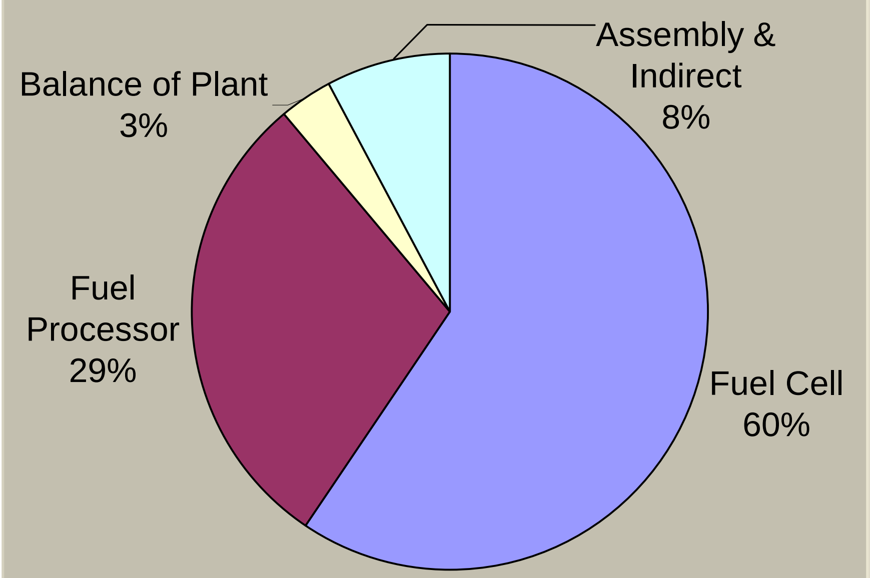
	Source Category	
	Manufactured	**Purchased**
Fuel Cell Module	◆ Unit Cell Components ◆ Assembly ◆ Testing	◆ Raw materials ◆ Perfluorosulfonic acid film ◆ Fuel Cell Hardware
Fuel Processor	◆ Packaging (containers, piping) ◆ Assembly	◆ Pump, valves, filters, fittings ◆ Sensors ◆ Catalysts ◆ Heat exchangers
Balance of Plant	◆ Packaging (containers, piping) ◆ Assembly	◆ Pump, valves, filters, fittings ◆ Sensors ◆ Catalysts ◆ Heat exchangers ◆ Compressor/Expander ◆ Batteries, regulator ◆ Control board ◆ Wiring harness

The estimated Year 2000 baseline fuel cell and fuel processor costs are approximately double the Year 2000 PNGV goal of $130/kW.

Sub-System	Factory Cost			
	Yr 2000 Estimate*		PNGV Goals($/kW)	
	($)	($/kW)	Yr 2000	Yr 2004
Fuel Cell	8,850	177	100	40
Fuel Processor	4,310	86	30	10
BOP	500	10	Not listed separately in PNGV Goals	
System Assembly	1,040	21		
Total	**14,700**	**294**	130	50

*Estimated accuracy ±20% ; Basis: 50 kWe net, 500,000 units/yr

Cost Breakdown by Sub-System



The system components were scaled by Year 2000 performance assumptions, but cost modeled at high production volumes.

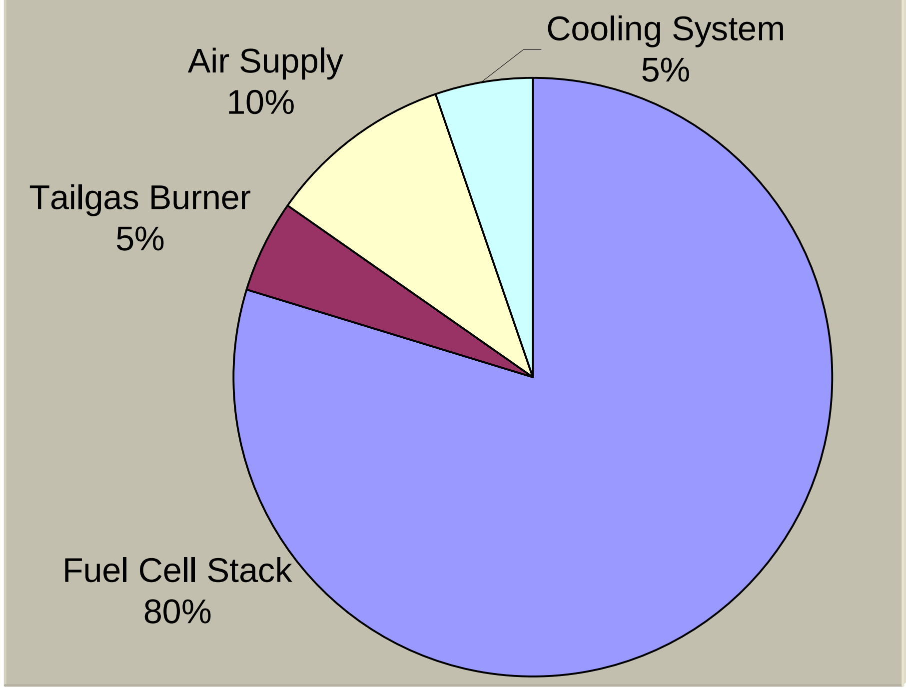
The fuel cell stack dominates the fuel cell sub-system cost.

Year 2000 Factory Cost		
Stack Sub-Systems	**($)**	**($/kW)**
Fuel Cell Stack	7,050	140
Tailgas Burner	460	10
Air Supply	860	17
Cooling System	480	10
Total	**$8,850**	**177**

PNGV Goal	**Yr 2000**	100

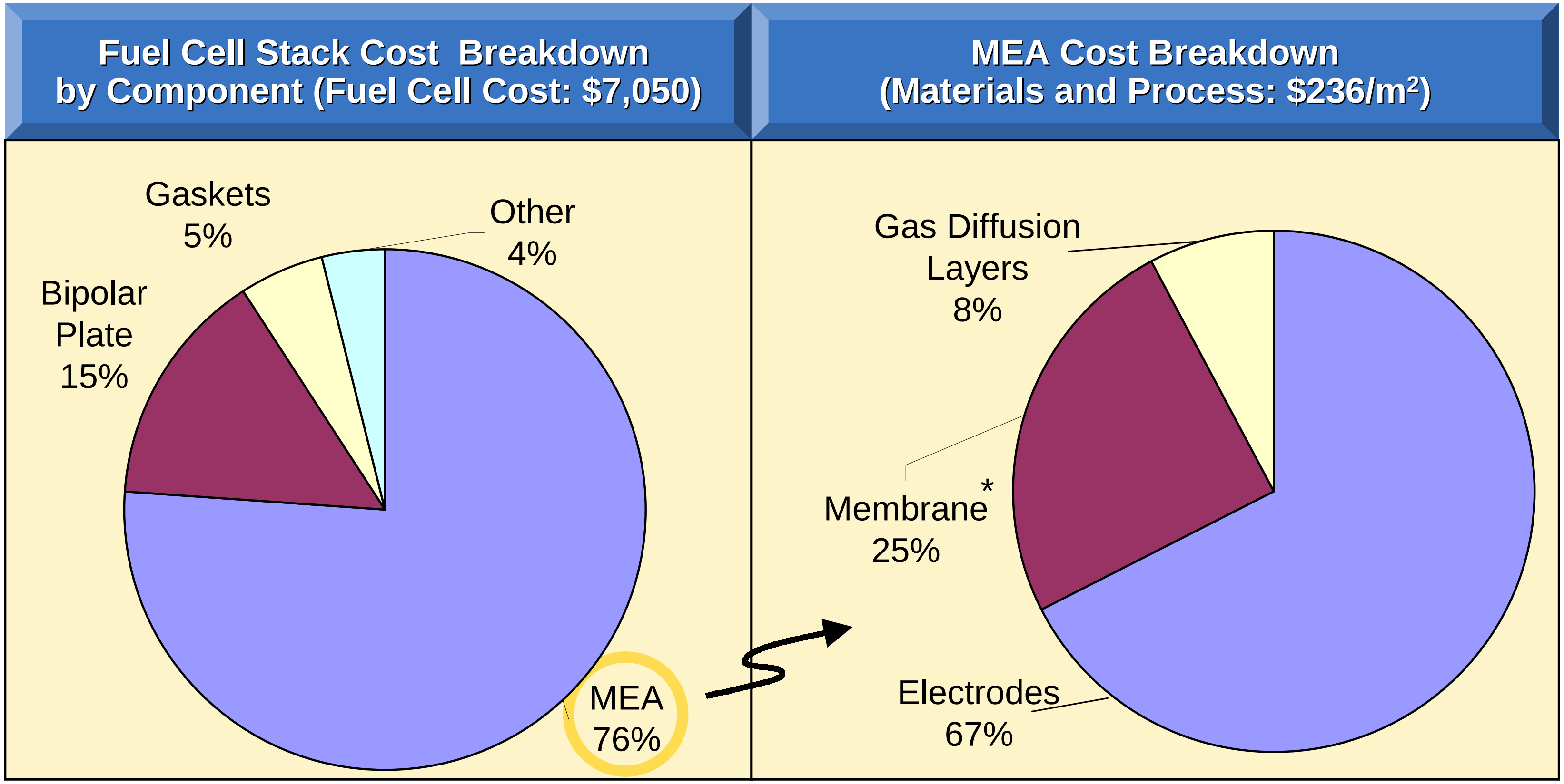
Basis: 50 kWe net, 500,000 units/yr

Fuel Cell Stack Sub-System Cost Breakdown (Cost: $8,850)



Important Assumptions: Combined anode and cathode Pt loading: 0.8 mg/cm^2 ; Ru loading on anode: 0.2 mg/cm^2; Power Density at 0.8 volts: 250 mW/cm^2

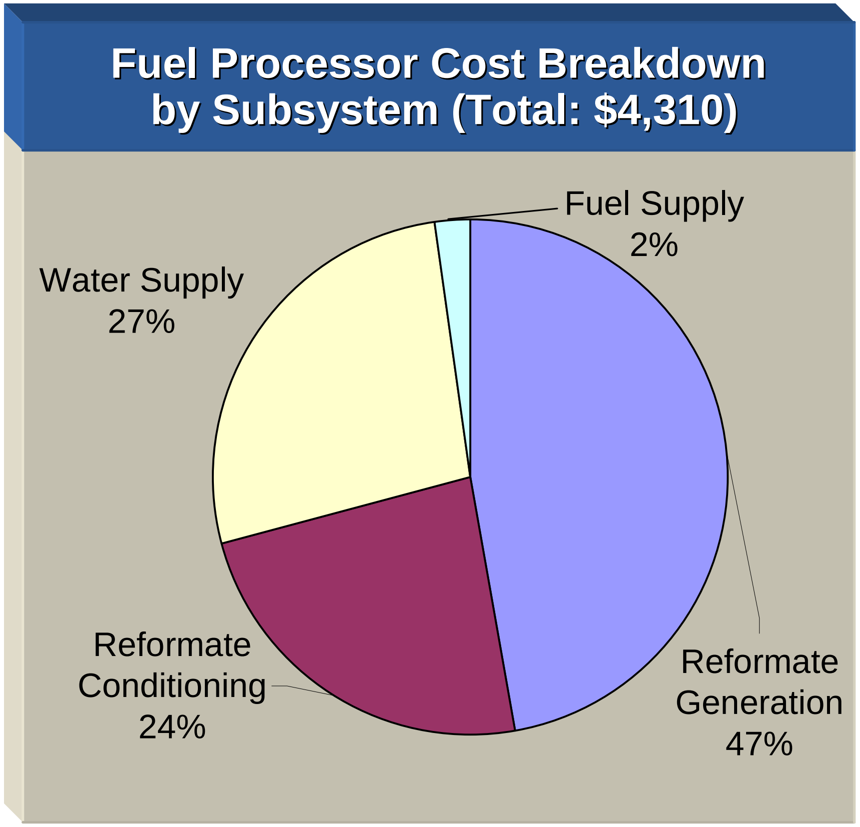
The membrane electrode assemblies (MEA) with their precious metal loading and polymer electrolyte dominate the cost of the fuel cell stack.



Basis: 50 kWe net, 500,000 units/yr; Total: Pt - 180 g, Ru - 45 g (50% MEA cost)
*Membrane priced at $55/m^2

Specification of a high efficiency (0.8V) design point for the fuel cell versus high power (0.6 V) approximately doubles the size and cost of the fuel cell.

The fuel processor sub-system represents approximately 35% of the system cost and is approximately three times the Year 2000 PNGV goal of $30/kW.

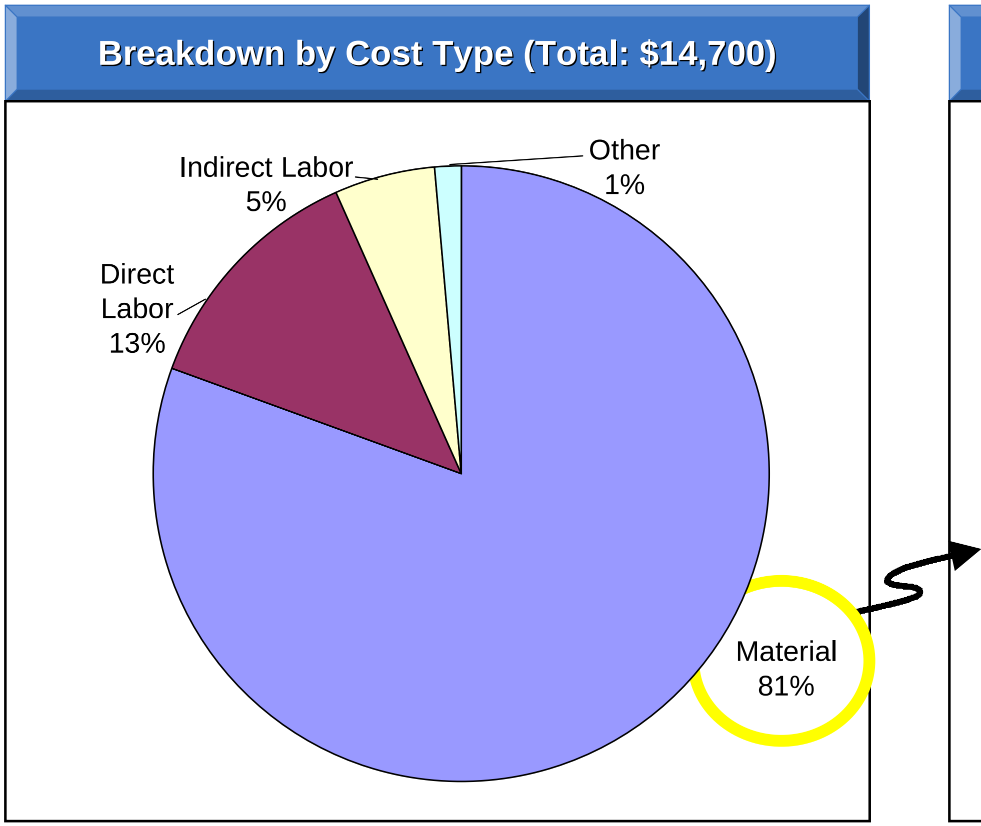


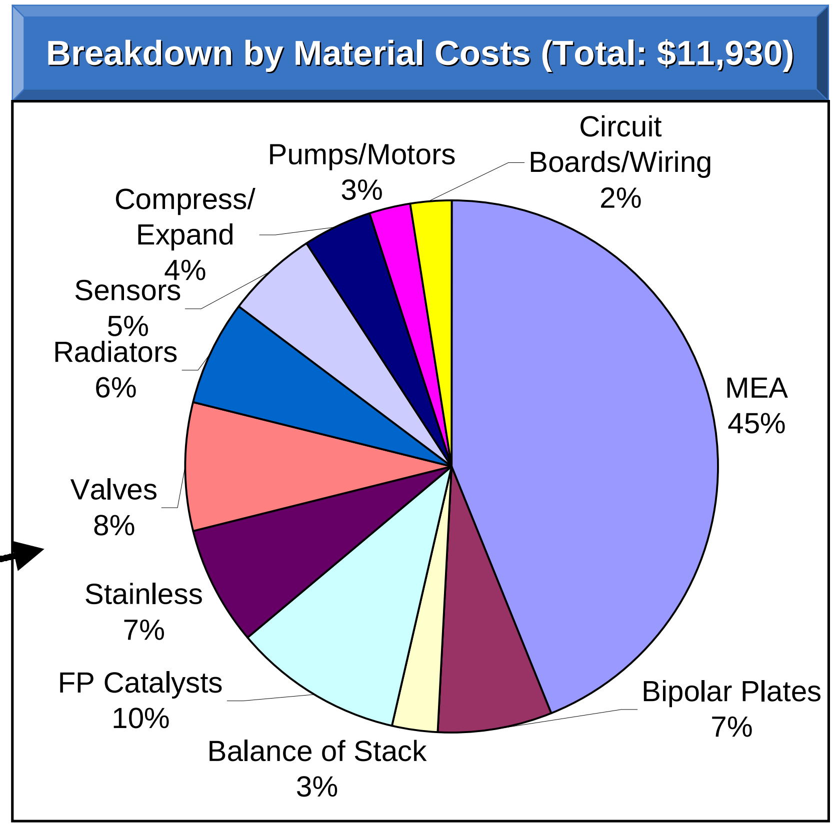
Basis: 50 kWe net, 500,000 units/yr

Fuel Processor Sub-System	Factory Cost ($)	Factory Cost ($/kW)
Reformate Generation	2,035	40
Reformate Conditioning	1,015	20
Water Supply	1,160	24
Fuel Supply	100	2
Total	**4,310**	**86**
PNGV Goal	**Yr 2000**	30

Not Complete without design assumptions

Performance advances which reduce component size and catalyst loadings will have major impact on system economics due to the significant materials contribution to cost.





***Purchased components from suppliers makeup approximately 25% of the material costs.**

Platinum pricing and loadings are significant factors in the economics of the fuel cell system. Platinum is approximately 20% of the total system cost at present loadings and fuel cell performance.

	ATR	PROX	Tailgas Burner	Fuel Cell MEA		
Precious Metal (PM)	Pt	Pt	Pt	Pt	Ru	
Bed Weight (kg)	3.2	14.8	2.9	---	---	
Loading %	0.5	0.2	0.5	---	---	
mg/cm²	---	---	---	0.8	0.2	**Total Pt**
PM Weight (g)	9	13	8	181	45	**211 g**
Cost*	$115	$175	$105	$2,450	$75	**$2,844**

* Based on Pt cost of $13.5 per gram

For the Year 2000 Baseline System, 500,000 vehicles would require approximately 52 metric tons of platinum.
(1995 Pt estimated reserves - 5,000 metric tons; 1996 annual production - 73 metric tons).

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In Year 2000, we will assess the opportunities for cost reduction through advances in component, system and manufacturing technologies.

- Present baseline cost model results to developers for feedback and discussion of potential improvements in performance and technology
- Develop advanced system configuration scenarios
- Model cost impact of technology advances
- Present results to developers for feedback
- Report cost model projections for advanced technology scenarios

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We have worked closely with the system modeling group of Argonne National Laboratory to arrive at the baseline system configuration. This effort has taken longer and involved greater effort than originally anticipated.

Task 1: **PEMFC System Technology Synopsis**

Task 2: Develop Cost Model and Baseline Estimates

Task 3: Identify Opportunities for System Cost Reduction

- Develop baseline system specification
- Project technology developments
- Assess impact on system performance
- Identify manufacturing processes

Projection of technology developments and assessment of their impact on system performance will be performed as part of Task 3.

DOE mandated several aspects of the Year 2000 baseline system specification. These have the potential to significantly impact system scale and cost.

- The system was designed to satisfy the PNGV efficiency goals at rated power, leading to the following model parameter inputs:
  - Cell voltage = 0.8V
  - Anode hydrogen utilization = 85%
  - Compressor efficiency = 70%
  - Expander efficiency = 80%
- The system was not modeled under simulated driving cycle conditions, where the vehicle spends a small percentage of the time at full power
  - Design at optimum power point would reduce size of fuel cell
- Must employ "today's technology"

The specification of 0.8 volt operating point at full power is a major departure from current practice where system developers have traditionally designed for maximum power to minimize the size of the fuel cell, and will be reexamined in Task 3.

DOE also mandated several other aspects of the system specification.

- Must be "fuel-flexible" with emphasis on gasoline
- Should use certain components:
  - Catalytic autothermal reformer
  - Turbocompressor, high speed motor (Allied Signal)
- System pressure equal to 3 atm.
- Must be water-sufficient
  - In the modeling process 95°F was selected as the ambient temperature design point
    - the design does not specifically address issues raised by operation at higher temperatures, e.g. in the Southwest

The PNGV technical committee strongly recommended that the ambient design temperature should be raised to at least 120°F. This will be done during Year 2000.

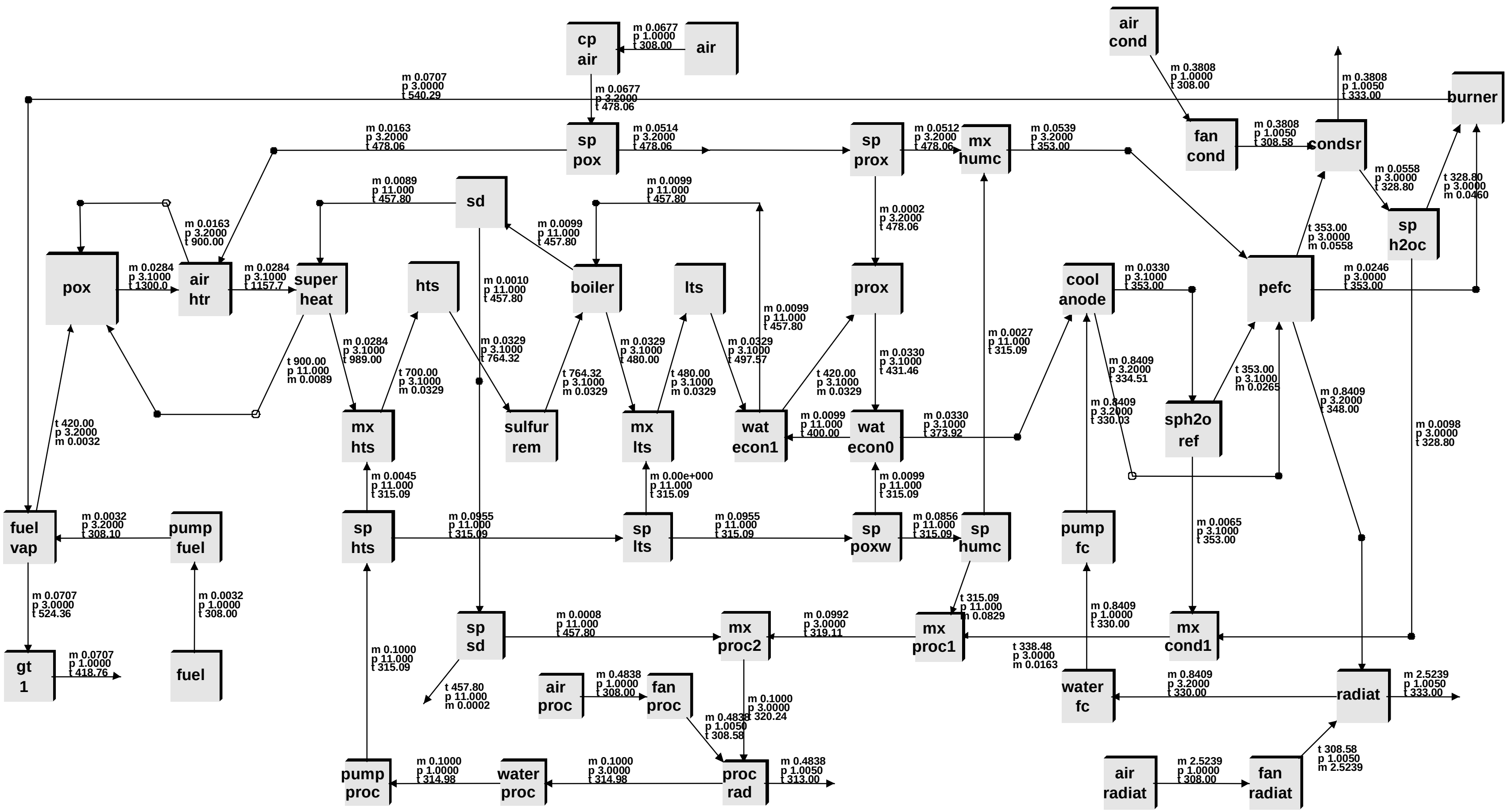
Arthur D. Little was not chartered to design a system which solves all of the problems now facing developers. The design does not address or fully address issues such as:

- Fast Startup (PNGV goals)
- Freezing Conditions
- Safety
- Operation below the design point
  - Some components may only provide quoted efficiencies at full power, e.g. the compressor/expander
- Components necessary to accommodate transients or start-up may be missing
- Not all control issues have been addressed, or even identified

Consideration of the above issues will increase the cost of the system.

The system model diagram below illustrates the complexity of the chemical system. The state points from this model were used to scale the system components.

Baseline 50-kW Design -- Gasoline Partial Oxidation PEM System



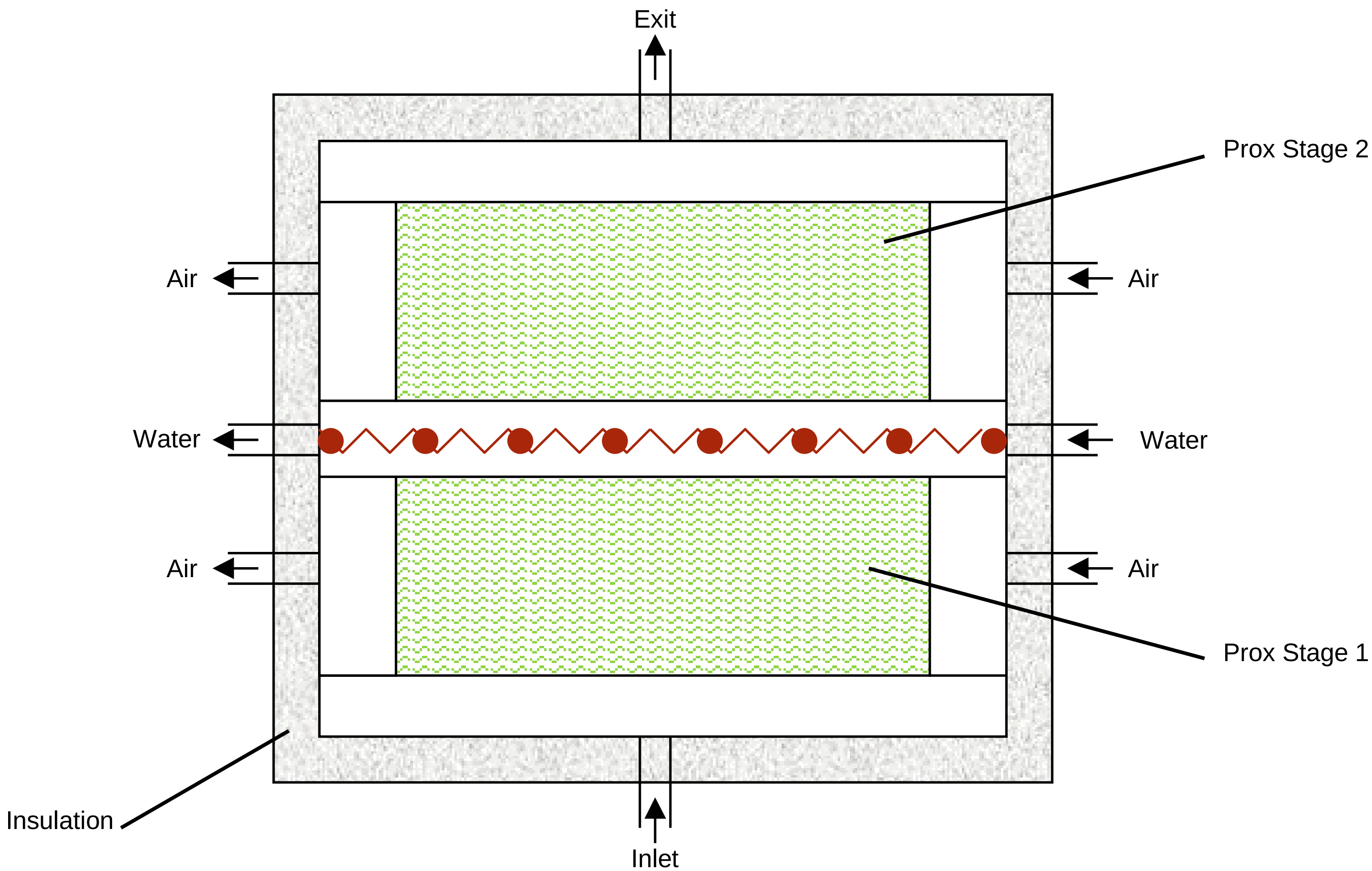
State parameters and mass/thermal flows calculated by Argonne National Laboratory
System configuration arrived at jointly by Arthur D. Little and Argonne National Laboratory

The table below summarizes the system efficiencies at full power.

	Based on HHV	Based on LHV
A. Fuel Value of "gasoline"	145.7 kW	135.8 kW
B. Fuel Value of H2 into PEM Fuel Cell	122.8 kW	104.0 kW
C. Cold Gas Efficiency of Fuel Processor [B/A]	84.3 %	76.5 %
D. Output from PEM Fuel Cell	56.5 kW	
E. Fuel Cell Efficiency [D/B]	46%	54%
F. Output from Expander	8.2 kW	
G. Parasitic Loads	14.3 kW	
H. System Efficiency [(D+F-G)/A]	34.6%	37.1 %
I. Radiator Rejected Heat	75.5 kW	

The overall efficiency for a drive cycle is estimated to be greater than 40% by ANL, however, the drive cycle efficiency will be heavily influenced by the efficiency of the compressor/expander at partial load.

A carbon bed absorber and multi-zone PROX reactor were used to clean up ammonia and CO from the reformate.

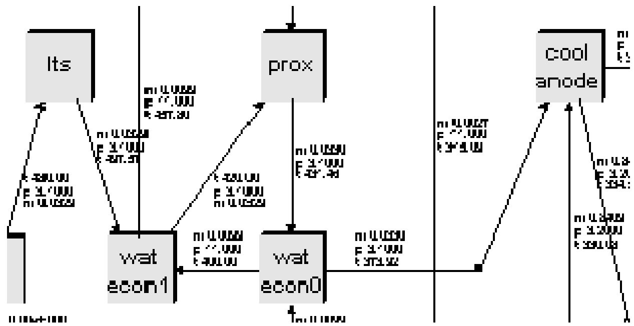


The ZnO sulfur removal bed is integrated into the reformate generator.

Current DOE system configurations do not include an ammonia scrubber.

- **PROX**
  - The PROX would have similar dimensions as an automotive catalytic converter (18"Lx5"D), except that
    - it would be chopped in half (the easy way) to make two stages
    - it would be built to withstand 30 psig
    - one must contrive to distribute air reasonably evenly in both stages
    - one must control the air flow to each stage, thus requiring two motor operated valves
    - one must contrive to control its temperature
  - Its catalyst could resemble, at least for costing purposes, the catalyst found in an automotive catalytic converter
- **Ammonia Cleanup**
  - Equilibrium calculations suggest the likelihood of ~150 ppm ammonia in reformate
  - This ammonia would likely harm the PEMFC in time
  - Ammonia can be removed from the anode inlet stream by passing it through a bed of activated charcoal
  - This bed requires no flow control valves, but it does require periodic replacement

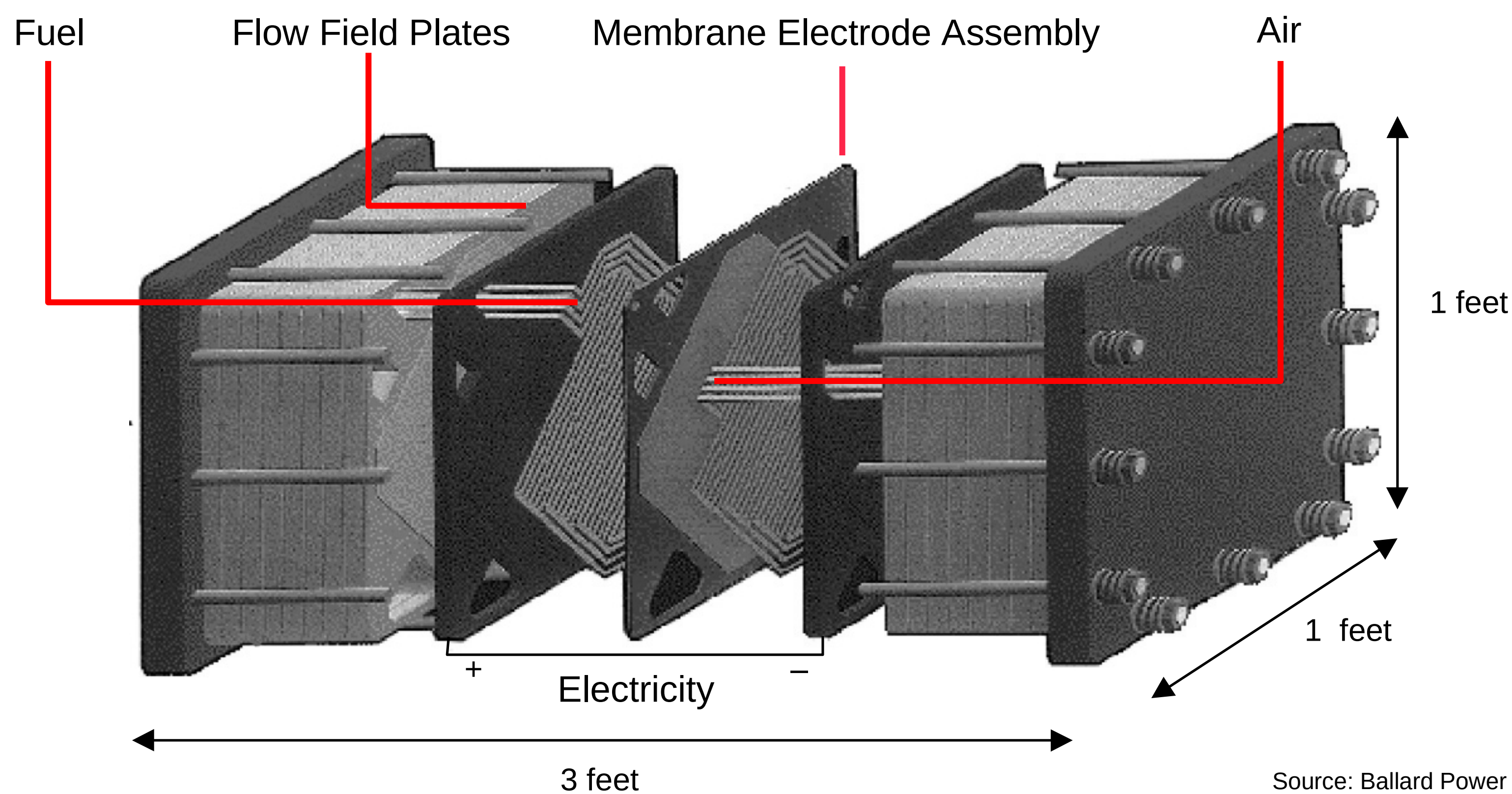
The economizers and the anode cooler are used to cool the reformate to the inlet temperatures of the PROX and the PEMFC.



HX	Duty		LMTD	Δp_{ref}	H	W	D	UA
	kBtuh	kW	°C	in wc	in	in	in	Btuh/°F
High temp economizer	13.5	4.0	29	7	4.25	6	32	259
Low temp economizer	12.2	3.6	44	3	4.25	6	12.5	154
Anode cooler	53.3	16	31	N/A	4.25	6	22	955

Indirect heat exchange was selected over water injection.

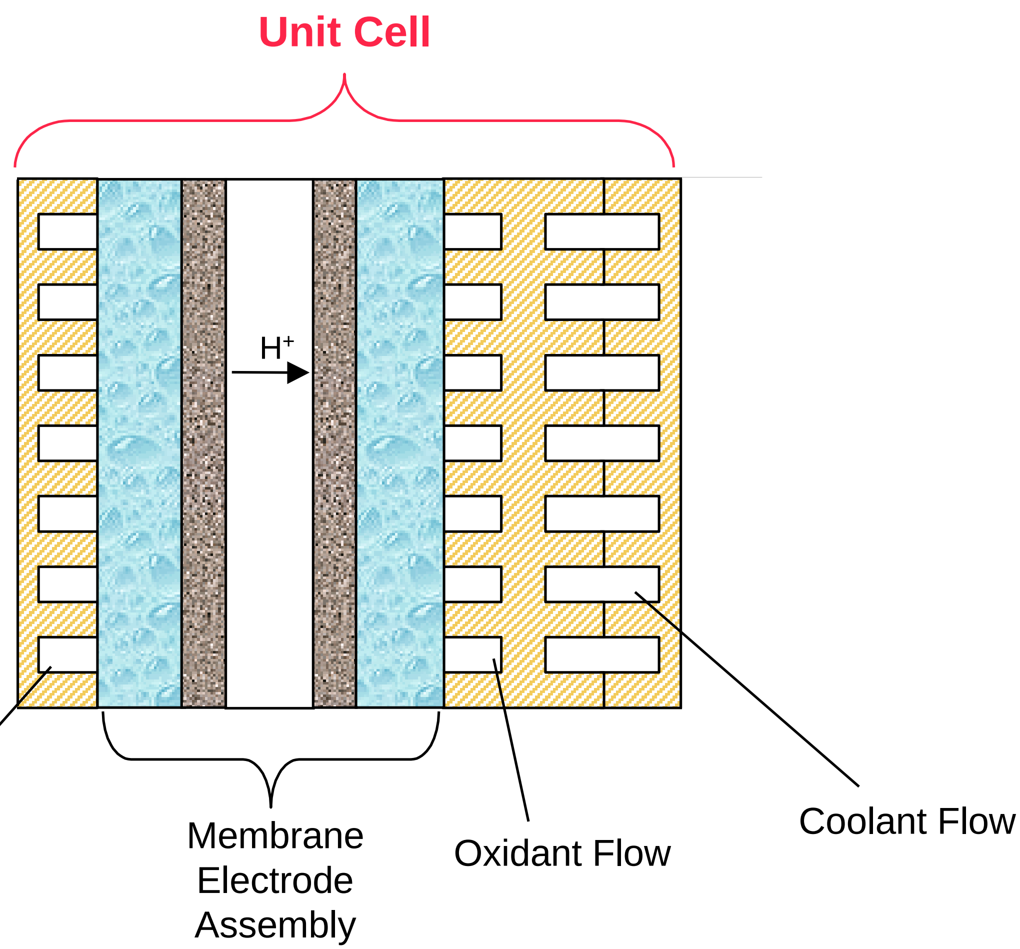
The fuel cell module is split into two stacks connected in series. Each stack is approximately 3 feet in length with 600 cm^2 active area per cell.



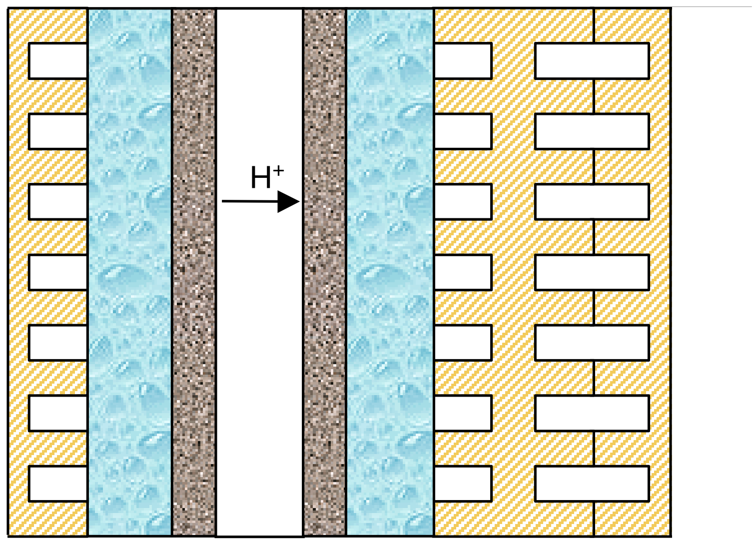
Source: Ballard Power Systems

A filter press type cell configuration with internal manifolds for all flow streams was adopted for costing the fuel cell.

We have used molded graphite/polymer composite* bipolar plates with integral cooling channels. The bipolar plate is molded in two pieces and bonded together.



We have used catalysts and catalyst loadings which correspond to demonstrated performance data.



Layer	Bipolar Plate	Gas Diffusion Layer- Anode	Anode	Electrolyte Membrane	Cathode	Gas Diffusion Layer - Cathode
Material	Graphite in Vinyl Ester	PTFE Treated Carbon Paper	Pt/Ru on Carbon Support	Perfluorosulfonic Acid	Pt on Carbon Support	PTFE Treated Carbon Paper
Thickness (um)	4750	100	20	40	20	100
Catalyst Loading (mg/cm^2)			Pt: 0.4 Ru: 0.2		0.4	

We have based our design on a pitch of 5 with one cooling plate per cell.

		ADL 1999
Electrochemical Layers	Anode (µm)	120
	Electrolyte (µm)	40
	Cathode (µm)	120
	Wt./area (g/cm^2)	0.36
	Vol./area (cm^3/cm^2)	0.08
Interconnect	Interconnect (µm)	4320
	Wt./area (g/cm^2)	1.29
	Vol./area (cm^3/cm^2)	0.43
Total Unit Cell	Wt./area (g/cm^2)	0.65
	Vol./area (cm^3/cm^2)	0.51
	Pitch (cells per inch)	5
	Density (g/cm^3)	1.3

Demonstration of fuel cell technology is progressing, but long-term performance on reformate must still be demonstrated/

- Long term performance (> 5000 hrs) with real reformate and ambient air (e.g. on roads) must be demonstrated
  - Anode and cathode catalyst stability in the presence of low concentrations of poisons (e.g. ppb levels)
- Increased power density while operating on *reformate* and at *high fuel utilization*.
- New membrane materials may allow operation at higher temperatures than allowed by the perfluorosulfonic acid membranes and lessen issues associated with water management.

The integrated tailgas burner, start-up steam generator, fuel vaporizer performs the following functions:

- It warms up the fuel processor.
- It disposes of the startup gases produced by the fuel processor once the fire is lit in the reformer but the reformate’s [CO] is not yet low enough to be allowed into the fuel cell.
- It removes energy from the combustible species in the anode tailgas stream.
- It assures low exhaust emissions
- It can vaporize fuel and water

The integrated tailgas burner contains three zones.

- **Burner Section**
  - A burner operating stoichiometrically on gasoline
  - Steam generating coils that also serve to quench this burner
- **Catalytic Burner**
  - A second, catalytic burner with more, embedded steam generating coils
  - Uses catalyst similar to automotive catalytic converter catalysts
- **Fuel Handling**
  - A fuel vaporizing section

The tailgas burner, start-up steam generator, fuel vaporizer's catalyst temperature must be maintained within a specific temperature window

- If it operates too hot, the catalyst is degraded
- If it operates too cold, it doesn't burn off the methane slip
- This implies the need for an sort of airflow modulating system, such as a temperature-controlled motor-operated valve

The tailgas burner is a major component, fully as large as any other package within the fuel processor, and generally less well understood.

We assumed that system and subsystem control will be accomplished by a single main controller.

- There could instead be a multiplicity of smaller controllers, but this would seem to serve no particular purpose.
- The controller board is one of those items that truly does decrease in cost with manufacturing volume, for most of its cost is the amortization of its development cost.
- The cost of the connectors, fuses and cooling could be greater than the cost of the controller board.
- The major portion of the cost of controlling will be:
  - Actuators (such as automatic valves)
  - Sensors (thermocouples are probably the least expensive of the sensors)
  - Signal conditioners (such as T/C A/D circuits)

We have identified the following sensors as being likely necessary:

- 16 temperature sensors, probably thermocouples, located throughout the system
- 1 oxygen sensor, located within the tailgas burner
- 1 sulfur sensor, located downstream of the ZnO bed
- 1 CO sensor, located downstream of the PROX
- 1 pressure sensor, located upstream of the backpressure regulator
- 1 ammonia sensor, located downstream of the activated charcoal bed
- 1 pH sensor, located within the process water system

- We anticipate that significant engineering and development effort will be required to eliminate these sensors or to significantly reduce their cost.
- We have not identified the additional sensors which might be required for safety.

Proportional control valves are necessary to control several critical process flows.

- Water Flows to
  - Reformate humidifier
  - Low temperature economizer (thence to steam generator)
  - Cathode air humidifier
  - Bypass anode cooler
- Air flow to
  - ATR (reforming zone)
  - Each section of the PROX
  - The anode inlet air bleed
  - Tailgas burner
- Back pressure regulator to maintain steam pressure
  - Maintains the pressure of the entire process water system.
  - Must be capable of having its setpoint adjusted remotely by the main controller, so that the CATR can maintain the appropriate steam/carbon ratio during power increase transients.

Cost effective control of gas streams at low flowrates needs to be developed.

Solenoid-operated diverter valves are necessary to accommodate transient and upset conditions.

- We use three way solenoid-operated diverter valves in the following locations:
  - Condensate in/out of steam generator
  - Steam in/out of steam generator
  - Process water pump discharge to humidifiers/warmup steam generator
  - Anode inlet stream to PEMFC/tailgas burner
- We use two way solenoid-operated valves where simple diversion isn't enough (where flow may need to go to both places at once)
  - Fuel to fuel vaporizer/start-up burner

There must be a startup battery of considerable capacity to provide power to the fuel processor during its warm-up period.

- It is not intended to power the vehicle during the fuel processor's warm-up period.
- A hybrid battery for transient power during driving and startup propulsion, if needed, will probably be an additional battery

	Full Expander Output		No Expander Output	
10 minutes parasitic loads	14.3 kW	2.4 kWh	14.3 kW	2.4 kWh
less 10 minutes expander	(8.2 kW)	(1.4 kWh)		
less 8 minutes radiator fan	(1.5 kW)	(0.2 kWh)	(1.5 kW)	(0.2 kWh)
net	4.6 kW	0.8 kWh	12.8 kW	2.2 kWh
# of 12VDC, 40 Amp-hr batteries discharged to 80% (25% margin)		**2**		**5.5**

The cost model assumes six batteries.

The "system" radiator will eventually consist of three separate circuits: the tailgas condenser, the process water cooler and the fuel cell cooler. For now, they have been sized as separate heat exchangers.

HX	Duty		LMTD	Δp_{air}	H	W	D	UA
	kBtuh	kW	°C	in wc	in	in	in	Btuh/°F
Tailgas Condenser	31.6	9.3	18	0.3	8.5	27	15	976
Process Water Cooler	7.5	2.2	7	0.2	10	23	1.5	598
Fuel Cell Cooler	216.8	64	20	0.5	21	55	3.75	6,022

- A higher power design point for the fuel cell cooler would require a larger fuel cell cooler.
- Increasing the ambient temperature design point (now 95°F) will increase the size of all the radiators.
- The fuel cell cooler is sized for an air side pressure drop of 0.5 inches, which is about what automotive fans can deliver. Were we to include the dynamic head of a moving vehicle, it could be a bit smaller.

The three air-cooled heat exchangers could perhaps be combined into a single heat exchanger that would be 24" high and 48" wide.

The thermal management system would also contain fans.

- The individual or integrated heat exchangers could be cooled by a pair of 24” diameter automotive-style fans
  - Each of these fans can move 3000 cfm of air against 0.5 in wc.
  - Each of these fans will require 350 watts of shaft power.

The fuel processor and fuel cell sub-systems account for approximately 80% of the overall system weight.

Fuel Cell Sub-System	
Components	**Weight (kg)**
Fuel Cell Stack	179
Tailgas Burner	38
Air Supply	15
Cooling System	63
Total	**295**

Fuel Processing Sub-System	
Components	**Weight (kg)**
Reformate Generator	114
Reformate Conditioner	52
Water Supply	47
Fuel Supply	2
Total	**215**

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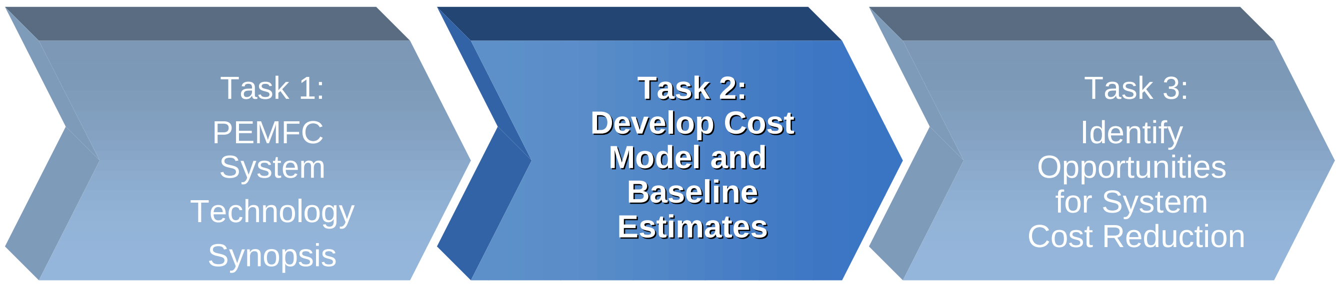
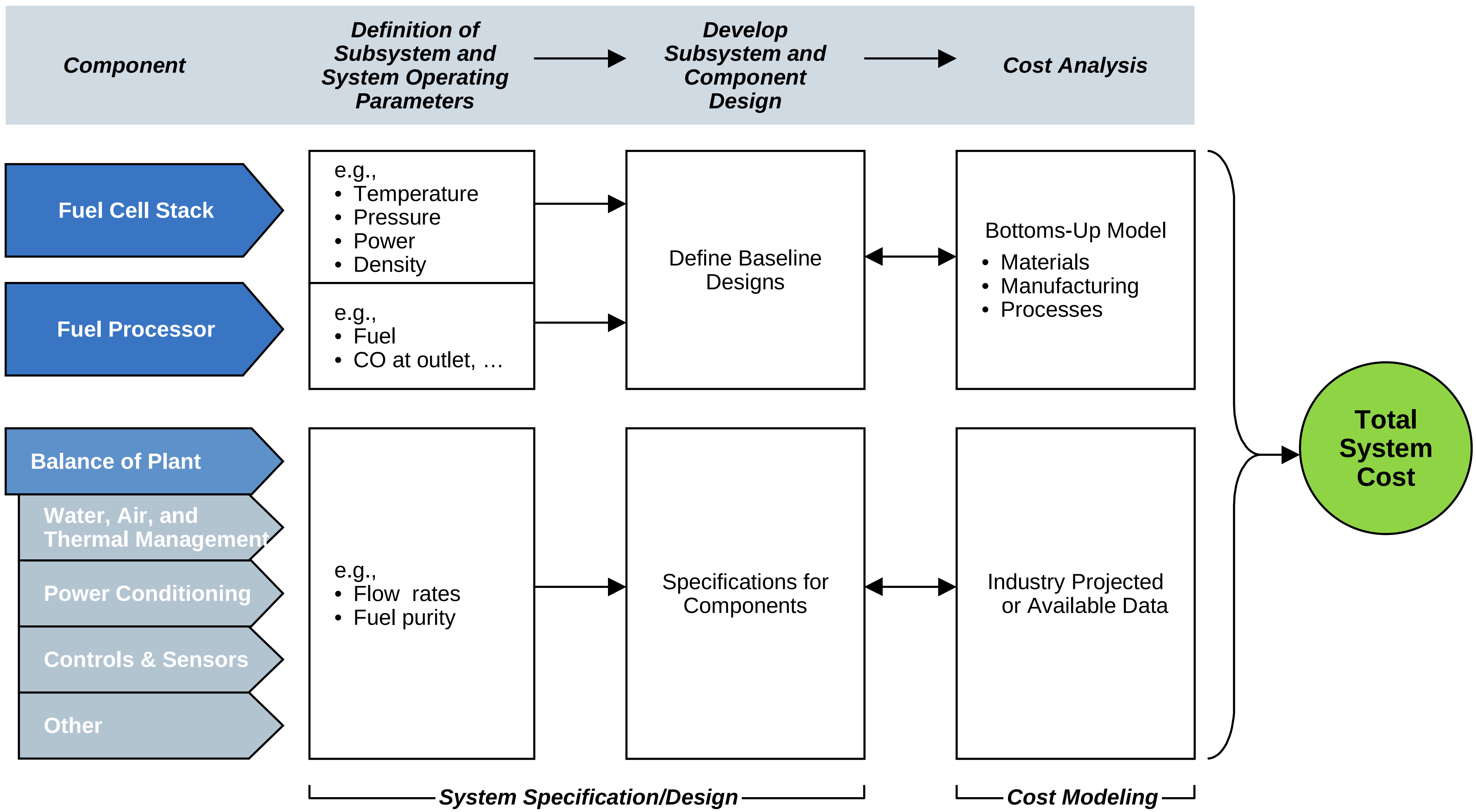
A cost estimate has been developed for the system specified in the Technology Assessment.



- Develop cost model
- Specify manufacturing processes and materials
- Develop production scenarios
- Baseline cost estimate

The cost model will be built on our fundamental understanding of the component subsystem technologies, and possible manufacturing processes.



The assumptions listed below impact the cost of the various systems

Fuel Processor	Fuel Cell	Other
ANL Catalyst Activities	250 mW/cm^2	Turbocompressor $500
Startup Time 10 minutes	300 V Stack	Net Parasitics 6 KW
100 ppm CO	600cm^2 active area	Max Ambient Temp 95 F
Vessel pressure safety factor 2.5 (not ASME)	Active Area 80% of Area	Stack Temp 80C
	Anode 0.2/0.4 Ru/Pt mg/cm^2	Negligible pressure drops in system
	Cathode 0.4 Pt mg/cm^2	
	Membrane $50/ m^2	

The design for high efficiency has a major impact on sizing of the fuel cell and consequently its cost.

The electrodes, electrolyte membrane, and bipolar plate dominate the cost of the fuel cell.

- $2.25 per lb was assumed for the high purity specialized graphite used in the bipolar plates
  - High volume (150,000 short tons assumed)
  - 99.99% pure materials now cost $1.75 - 2.00 per lb

Stack Costs		Active Area Basis[1] Mtl Cost ($/m²)	Process Cost ($/m²)	Total Cost ($/m²)	Unit Cell Weight/Area (g/cm²)	Total Fuel Cell Module Weight	Total Fuel Cell Module Mtl Cost ($)	Total Fuel Cell Module Process Cost ($)	Total Fuel Cell Module Cost ($)	Total Fuel Cell Module Cost ($/kW)
MEA	Anode GDL	$8.81	$0.48	$9.29	0.021	5.09	$200	$11	$211	$4
	Anode Active Layer	$80.58	$2.11	$82.69	0.002	0.09	$1,828	$48	$1,875	$38
	Electrolyte	$56.13	$1.78	$57.91	0.008	1.78	$1,273	$40	$1,313	$26
	Cathode Active Layer	$75.20	$1.98	$77.18	0.002	0.00	$1,706	$45	$1,750	$35
	Cathode GDL	$8.81	$0.48	$9.29	0.021	5.36	$200	$11	$211	$4
MEA Total		**$229.51**	**$6.84**	**$236.35**	**0.054**	**12.33**	**$5,206**	**$155**	**$5,361**	**$107**
Bipolar Interconnect[2]		$37.19	$8.48	$45.67	0.584	133.13	$844	$192	$1,036	$21
Gaskets						2.52	$142	$234	$376	$8
End Plates						4.05	$17	$2	$19	$0.4
Current Collector						10.12	$25	$1	$26	$1
Insulator						2.05	$48	$1	$49	$1
Outer Wrap						10.98	$35.5	$2.8	$38.4	$0.77
Tie Bolts						4.42	$37	$2	$40	$1
Final Assy								$106	$106	$2
Total Unit Cell		**$266.70**	**$15.32**	**$282.02**	**0.638**	**179.60**	**$6,354**	**$697**	**$7,051**	**$141**

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The listed goals pertain to a gasoline fueled flexible fuel system which includes fuel processor, fuel cell stack, and auxiliaries but excludes the gasoline tank and DC-DC converter.

Characteristic	Units	Calendar Year		
		1997	2000	2004
Energy Efficiency @ 25% peak power	%	35	40	48
Power Density	W/L	200	250	300
Specific Power	W/kg	200	250	300
Cost	$/kW	300	150	50
Startup to full power	min	2	1	0.5
Transient Response (time from 10 to 90% power)	sec	30	20	10
Emissions		<Tier 2	< Tier 2	< Tier 2
Durability	hour	1000	2000	5000

The PNGV stack definition also includes fuel cell ancillaries: i.e., heat, water, air management systems

Characteristic	Units	Calendar Year		
		1997	2000	2004
Stack system power density (net power)	W/L	300	350	500
Stack system specific power	W/kg	300	350	500
Stack system efficiency @ 25% peak power	%	50	55	60
Stack system efficiency @ peak power	%	40	44	48
Precious metal loading	g/peak kW	2.0	0.9	0.2
Cost (500,000 units per year)	$/kW	200	100	35
Durability (< 5% power degradation)	hour	>1000	>2000	>5000
Cold Startup to max. power 20oC	min	2	1	0.5
CO tolerance (steady state)	ppm	10	100	1000
CO tolerance (transient)	ppm	100	500	5000

The fuel processor includes controls, shift reactors, CO clean-up, and heat exchangers.

Characteristic	Units	Calendar Year		
		1997	2000	2004
Energy efficiency	%	70	75	80
Power Density	W/L	400	600	750
Specific Power	W/kg	400	600	750
Cost (500,000 units per year)	$/kW	50	30	10
Transient response (time from 10 to 90% power)	sec	30	20	10
Start-up to full power	min	2.0	1	0.5
Durability (< 5% power degradation)	hour	>1000	>2000	>5000
H2S content in product stream NH3 content in product stream	ppm	0 <10	0 <10	0 <10
CO content steady state	ppm	100	10	10
CO content transient	ppm	5000	500	100

Fuel Processor efficiency = total fuel cell system efficiency/fuel cell stack system efficiency, where total fuel cell system efficiency accounts for thermal integration