

DFMA Cost Estimates of Fuel-Cell/Reformer Systems at Low/Medium/High Production Rates

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Full Presentation available at:

www.DirectedTechnologies.com

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Laboratory.**



Outline

1. Project Goals and Scope
2. System Design Overview
3. Results and System Cost Estimates
4. Conclusions

Project Goals

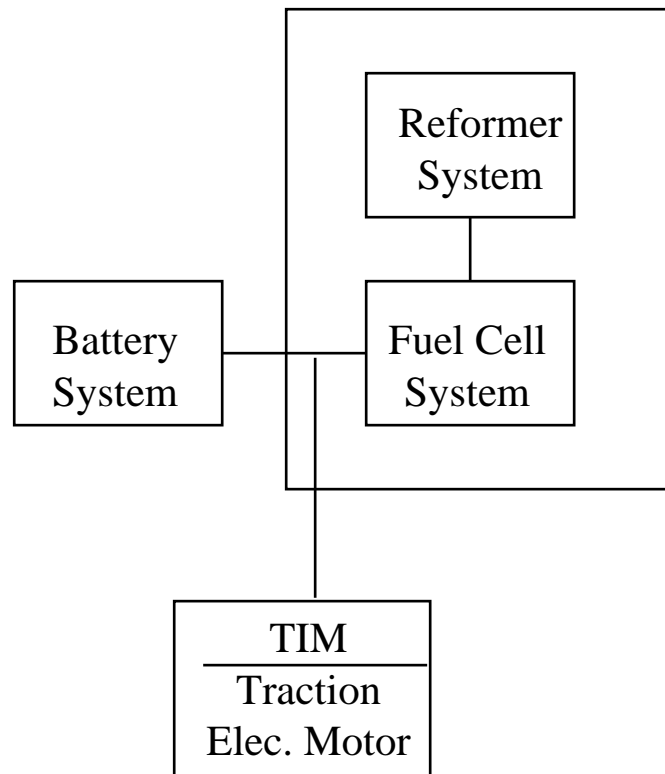
- 1. Identify the lowest cost system design and manufacturing methods :**
 - for automotive gasoline fuel processor and a polymer electrolyte membrane (PEM) fuel cell system
 - Use DFMA redesign and costing techniques
- 2. Determine costs for system production rates:**
 - 500 vehicles per year
 - 10,000 vehicles per year
 - 30,000 vehicles per year
 - 500,000 vehicles per year
- 3. Use cost results to guide future component development**

Project Approach

- 1. Base on detailed, rigorous and consistent system design**
 - A. Begin with System modeling (Hysys environment)
 - B. Design each component (materials, dimensions, thickness, etc.)
 - C. Use DFMA redesign and costing techniques
 - DFMA= Design for Manufacturing & Assembly*
 - Adjust for manufacturing rates (material cost, lot size, setup costs, manufacturing methods, markup rates, etc.)
- 2. Consider Year 2001 technology** (i.e. no dramatic forward projections)
- 3. Emphasis realistic and complete cost assessment**

* DFMA is a registered trademark of Boothroyd Dewhurst Inc.

Scope of Project



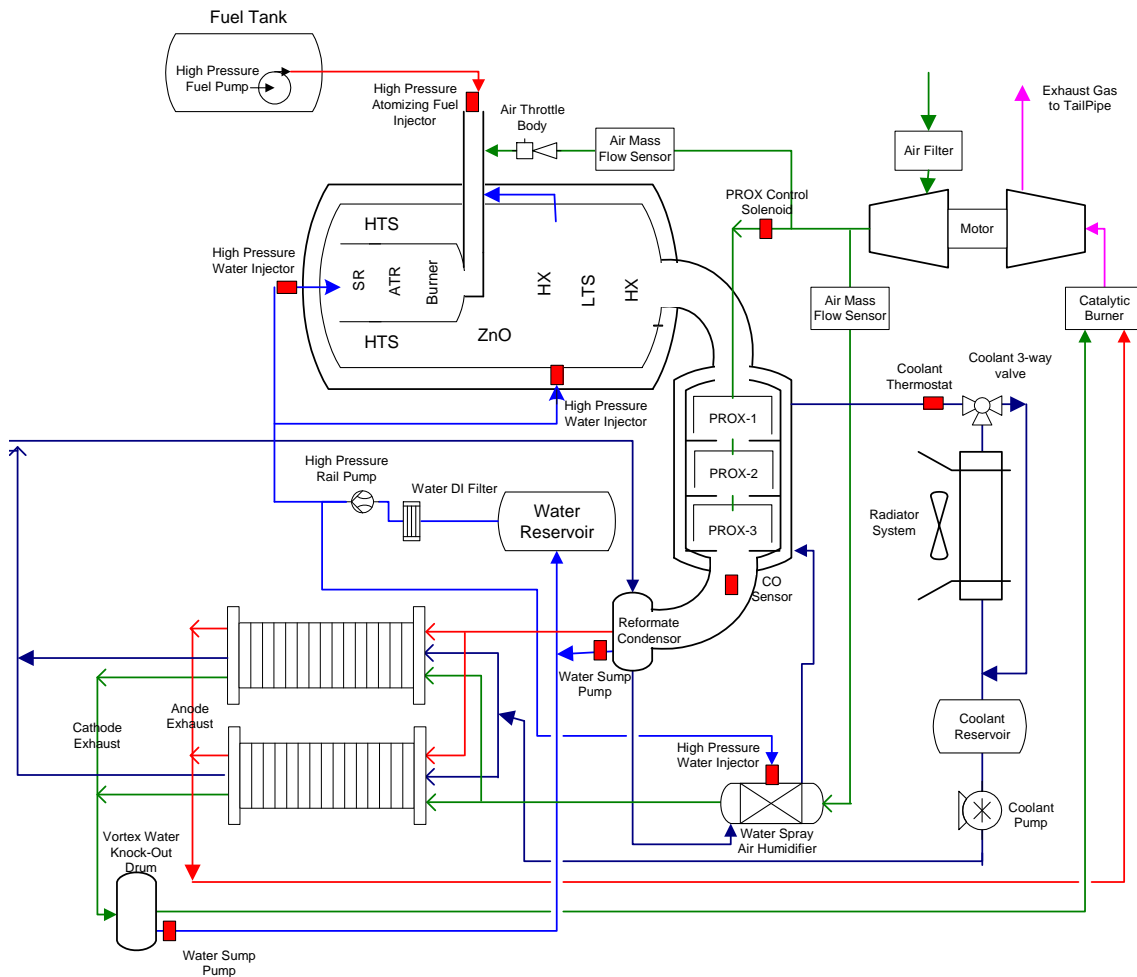
What is included in Project:

- Reformer
 - Fuel vaporizer
 - Burner
 - Reformer
 - Shift beds
 - Gas cleanup
- Fuel Cell System
 - Fuel cell stacks
 - Air supply and humidification
 - Thermal management
 - Water management
- Fuel Supply System
- Power conditioning and electronics (for FC/Ref. Only)
- Electrical System
- Control System
- Sensors
- Safety Systems

What is not included in Project:

- Traction Inverter Module (TIM)
- Traction Electric Motor
- Peak-Power/Start-Up Battery

ATR Year 2001 Baseline



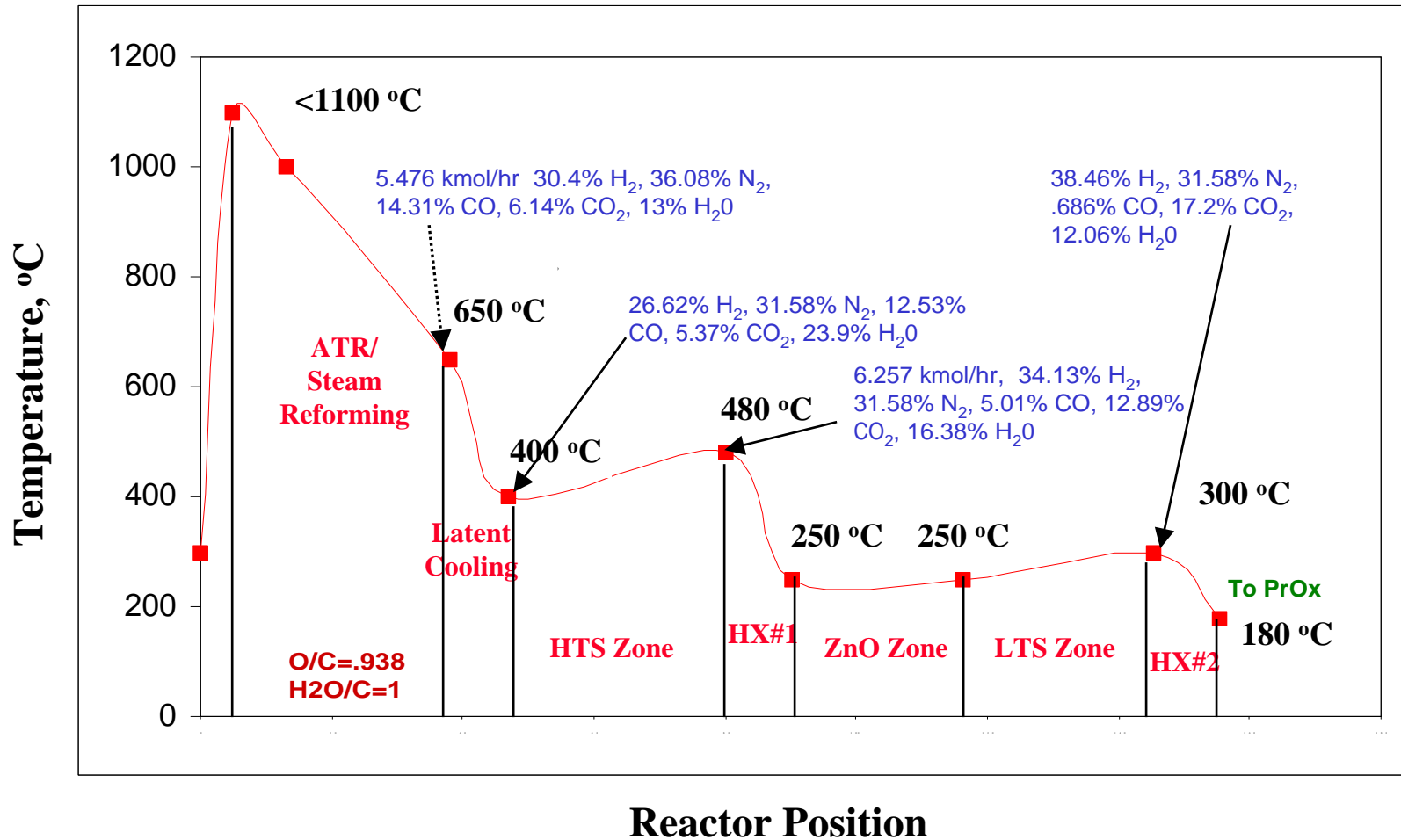
Main System Features:

- Tier 2 Gasoline (30ppm S average)
- ATR (Auto Thermal Reformer)
 - ATR catalyst
 - HTS catalyst
 - ZnO bed for Sulfur removal
 - LTS Catalyst
- 3-Stage Preferential Ox. (PrOx) Unit
- Reformate PEM Fuel Cell
- Catalytic Burner
- Exhaust Gas Expander/Air Compressor

PDF for ATR System V2_2.vsd
 Directed Technoloiges Inc.
 30 May 2001



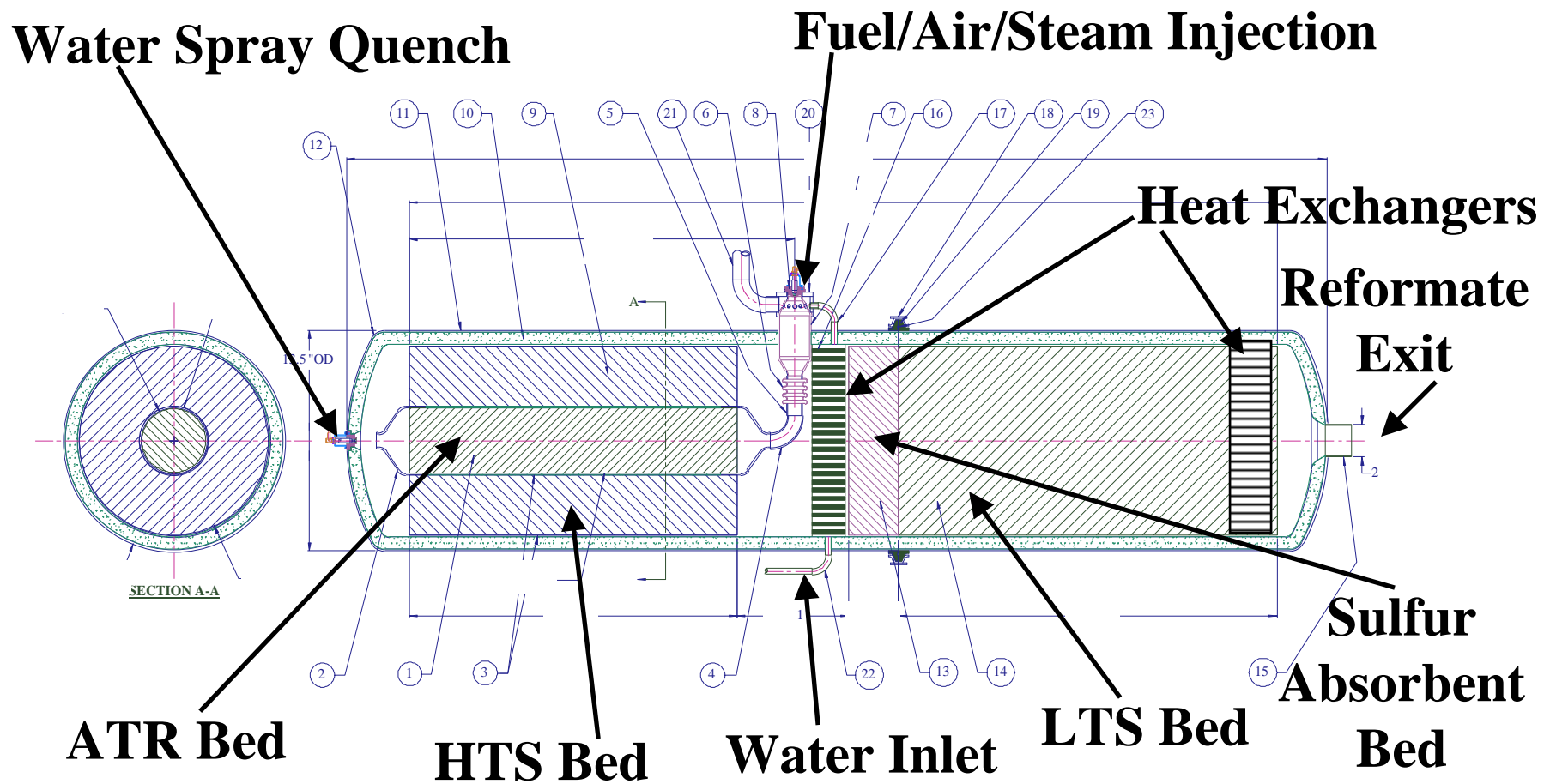
Baseline ATR Operating Temperatures



Feeds (before preheat): 3.762 kmol/hr, 150 °C

0% H₂, 13.96% O₂, 52.53% N₂, 0% CO, 0% CO₂,
29.78% H₂O, 3.722% Octane

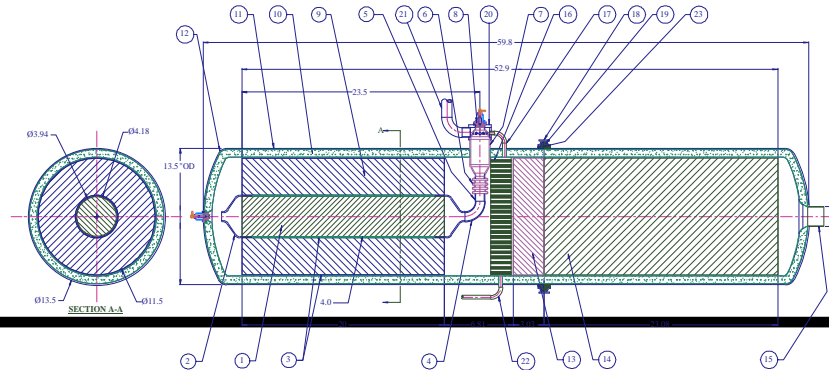
ATR Concept Sketch



Sketch NOT to scale

ATR Catalyst Summary

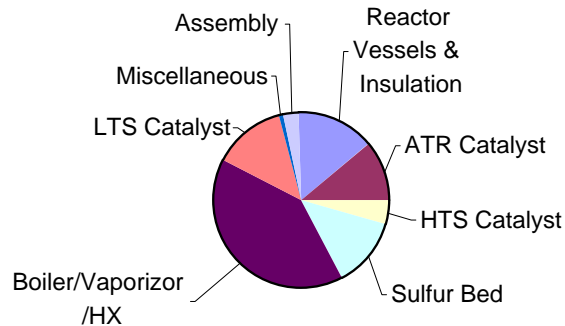
	ATR		HTS	ZnO	LTS	Vaporizer/ Boiler
Volume	0.9 L	2.8L	2.3L	7.3L	8.1L	2.6L
Support	Discs of Zirconia Foam	Zirconia Toughened Mullite Extrudate	600cpi Cordierite extrudate	Cordierite Extrudate/ Zirconia Foam	600cpi Cordierite Extrudate	Finned Plate HX, 316 L, two required
Catalyst	0.4% Pt (surrogate for ANL proprietary catalyst)		0.14% Pt on gamma alumina	Zinc Oxide/CuO Absorbent	ANL Cu/O catalyst	-
500 units/year	\$73	\$263	\$125	\$360	\$383	\$1,226
500k units/year	\$40	\$114	\$68	\$177	\$195	\$302



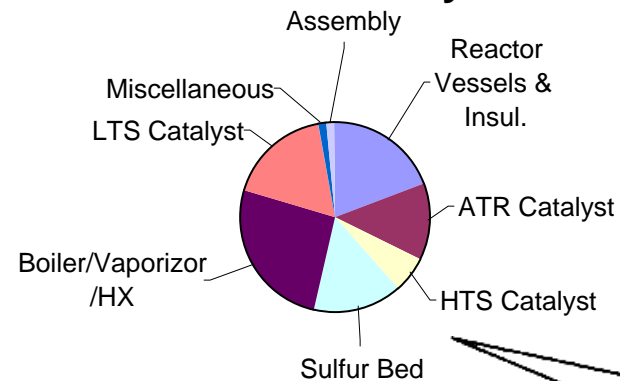
ATR Reactor Cost Summary

	Annual Production Rate			
	500	10,000	30,000	500,000
1 Reactor Vessels & Insul.	\$443	\$288	\$268	237
2 ATR Catalyst	\$346	\$202	\$176	\$159
3 HTS Catalyst	\$131	\$89	\$75	\$71
4 Sulfur Bed	\$369	\$243	\$199	\$186
5 Boiler/Vaporizor/HX	\$1,253	\$558	\$374	\$317
6 LTS Catalyst	\$420	\$278	\$230	\$218
7 Miscellaneous	\$26	\$20	\$16	\$15
8 Assembly	\$92	\$26	\$24	\$19
10% Cost Provision	<u>\$308</u>	<u>\$170</u>	<u>\$136</u>	<u>\$122</u>
Total	\$3,389	\$1,874	\$1,498	\$1,343

Cost at 500 units/year



Cost at 500k units/year

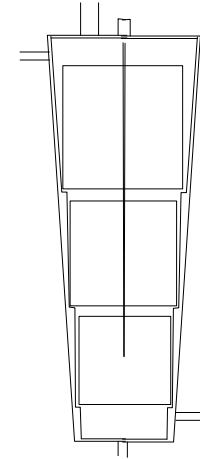


PrOx Cost Summary

3-Stage Unitized PROX

Cost Basis and Major Assumptions:

- 120 kW_{thermal} (LHV) hydrogen throughput, (for 50 kW_{electric} FC system)
- 1% CO inlet concentration, 25-50 ppm CO outlet concentration
- Based on LANL concept with mods for manufacturability.
- Assumes air valve to meter air to each of three PROX stages
- Cost based on 0.3% (by wt) Pt catalyst on cordierite substrate.
- Catalyst/alumina washcoating of cordierite monolith as per industrial practice (automotive catalytic converters).



	Annual Production Rate			
	500/yr	10k/yr	30k/yr	500k/yr
Materials	\$219	\$172	\$154	\$142
Manufacturing	\$133	\$27	\$20	\$17
Assembly	\$153	\$28	\$22	\$16
Total PROX Cost	\$505	\$227	\$196	\$175

Fuel Cell Stack

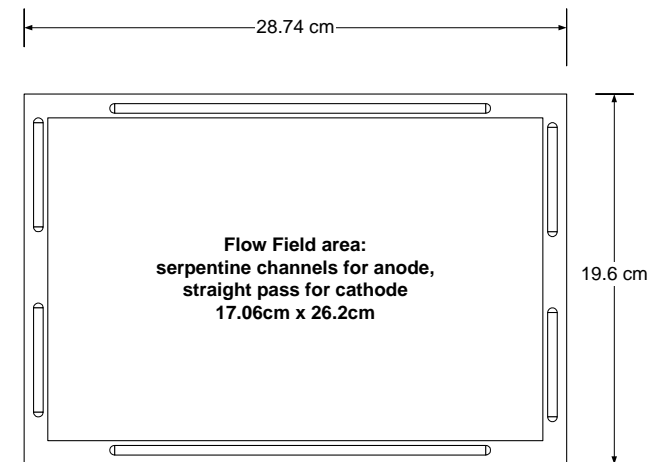
- **Operation on Reformate Fuel**

- Nominally: 38% H₂, 32% N₂, 18% CO₂, 12% H₂O (Mole Fractions)

- And < 50 ppm CO

- **2 atm nominal operating pressure at peak power**

	Reformate System Baseline
<u>Peak Power</u>	
Gross kW	55 kW
Net kW	50 kW
Cell Voltage	0.7 volts
Current Density	400 mA/cm ²
Power Density	280 mW/cm ²
Number of Stacks	4
Number of cells per stack	110
Total number of cells	440
Total active membrane area, m ²	19.64 m ²
Active area per cell, cm ²	446 cm ²
Peak voltage (at 0.92 v/c)	405 volts
Min voltage (at peak power)	308 volts
Max Current (at peak power)	178.6 amps



Catalyst Loading:

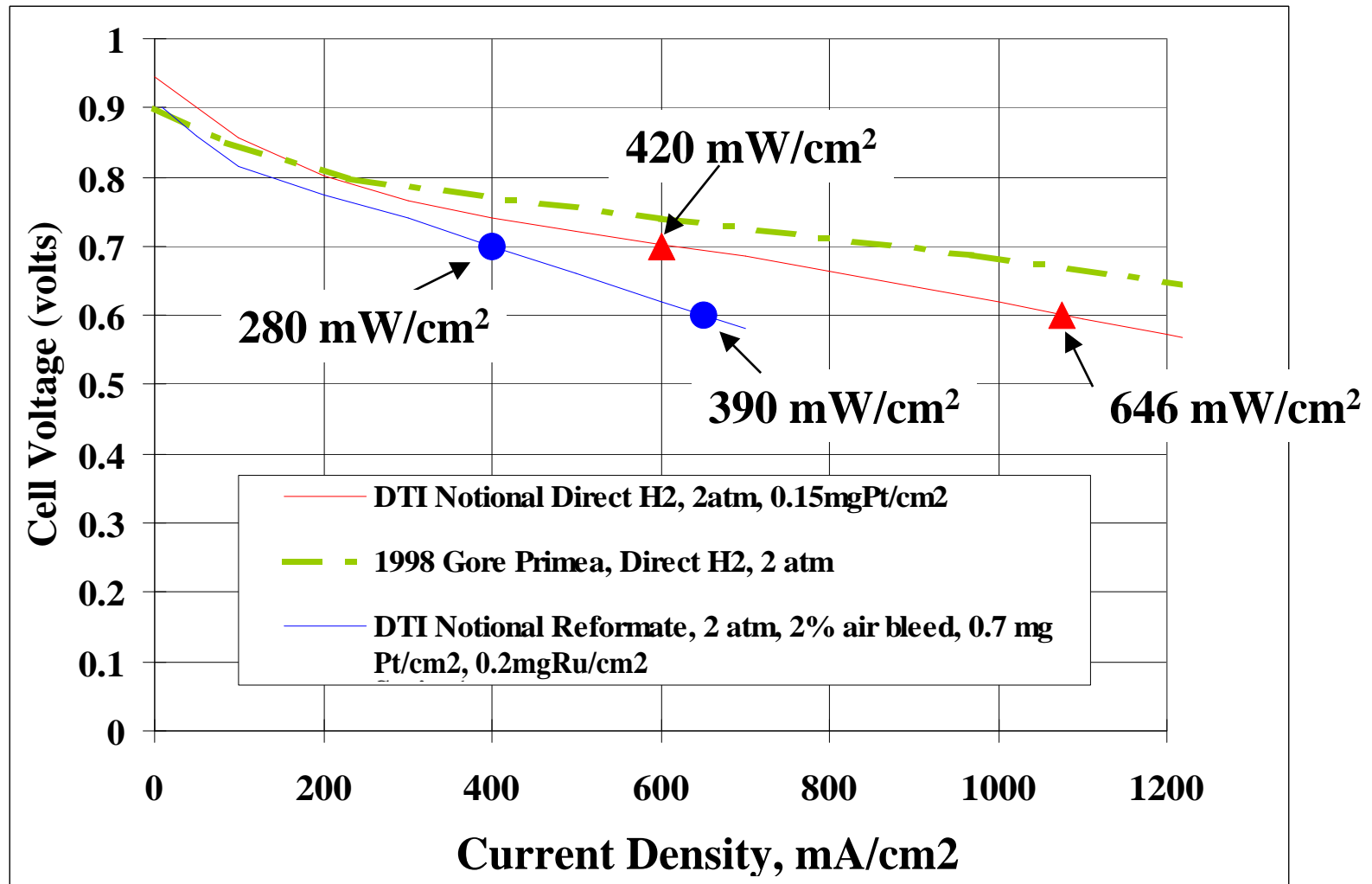
Cathode 0.3 mg Pt/cm²

Anode 0.4 mg Pt/cm²

0.2 mg Ru/cm²



Polarization Performance



Fuel Cell Stack Assumptions

- **Bipolar Plate Production/Materials**

- Injection Molded, carbon black filled composite (60% polypro, 40% carbon)
(EP-like approach)

- **Current Collectors**

- Aluminum blankings

- **Electrical Insulator Plates**

- Injection molded polypropylene

- **Endplates**

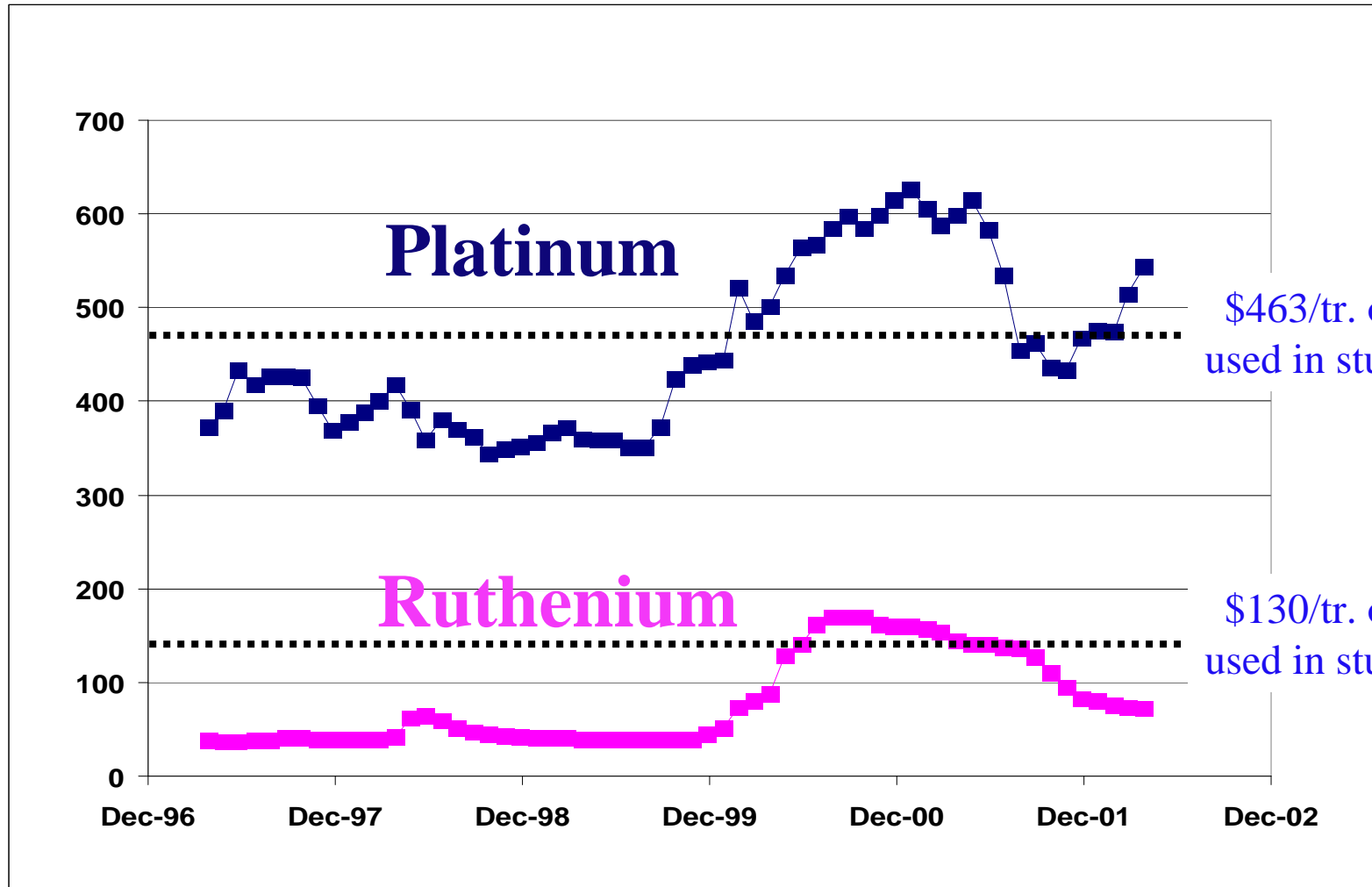
- Aluminum die-castings
- machining more costly at all production rates studied

- **MEA's**

- membrane, GDL hot pressed together in polypro frame
- follows method of Kelland at Analytic Power
- catalyst ink composition and costs
- ionomer

Precious Metal Costs Fluctuate

Monthly Average US\$/Troy Ounce



Membrane and MEA Assumptions

• Membrane Baseline:

- Build-off previous DTI Converting Machinery MEA Process Train
- Also considered
 - Table Casting of homogeneous ionomer
 - Hot Melt Extrusion (DuPont)
- Other Options potentially explored later (electro-static spray, others)

• Catalyst Ink composition:

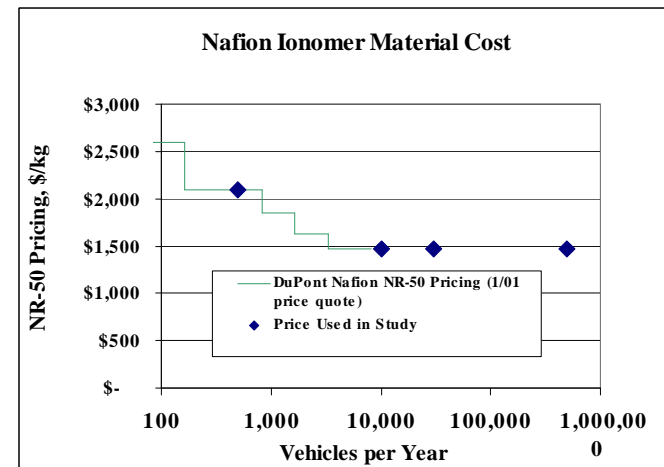
- Carbon support Pt (or Pt/Ru) (based on 20% Pt on Vulcan X-72), ionomer, water (or glycerin) [Mass ratio of approximately 0.2/0.33/5(or 20)]
- Catalyst prep costs based on hexachloroplatinic acid (CPA) precursor and notional E-TEK-like precipitation method

• Ionomer:

- DuPont NR-50 Super Acid
- Price quote obtained 1/01
- High production ionomer cost not fully reflected

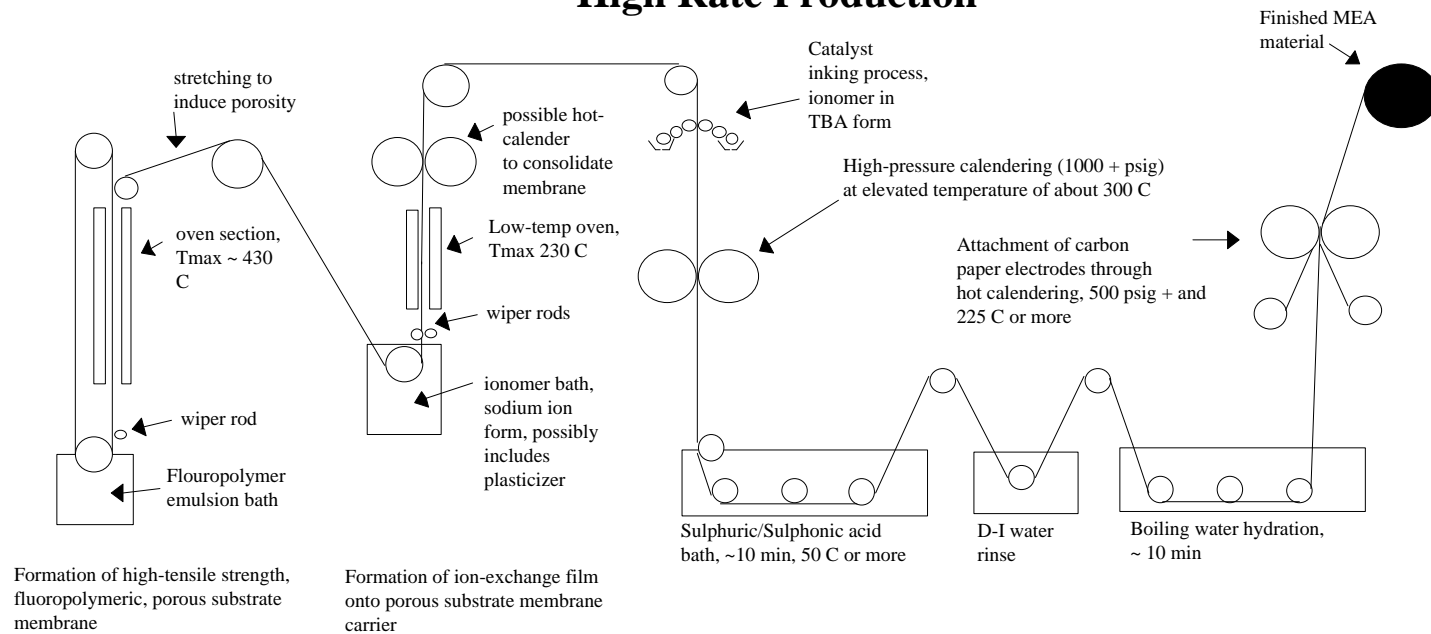
• Gas Diffusion Layer (GDL):

- Based on Spectra Corp. mass production estimate



Fully-Automated, Continuous MEA Process Train

High Rate Production



Initial bath casting onto a continuous, high-temperature polymer belt. Feed rate limited to 10 - 30 fpm by size of practical oven. Substrate membrane is peeled from the continuous belt then stretched. Stretching of partially crystallized fluoropolymer (50% - 70%) along the axis of the substrate membrane with or without additional heating. Stretching will increase the linear feed rate by a factor of 2 or greater, and result in a highly-porous substrate membrane of controlled thickness. Ionomer emulsion or solution is cast onto the web then dried and cured in an oven or hot-calendered to ensure proper consolidation. Because the ionomeric material requires lower temperatures than the fluoropolymer, high speeds should be attainable. The result is a composite ion-exchange membrane with the ionomer in the sodium ion form.

Metering bars or equivalent means are employed to add the appropriate amounts of both anodic and cathodic ink in an emulsion with the tetrabutyl ammonium (TBA) form of the ionomeric material and a carrier of dimethyl sulfoxide or other appropriate material. The inked membrane is then hot-calendered at a temperature and pressure sufficient to effect proper mating between the catalysts and the membrane. The membrane is then protonated, rinsed, and hydrated. The final step is hot calendaring the carbon paper electrodes to the catalyzed membrane, which might also include hydrophobic doping with a fluoropolymer.

Schematic View, Not to Scale

Mass Production Estimate: \$1-8/m² (manufacturing cost, fully marked up)

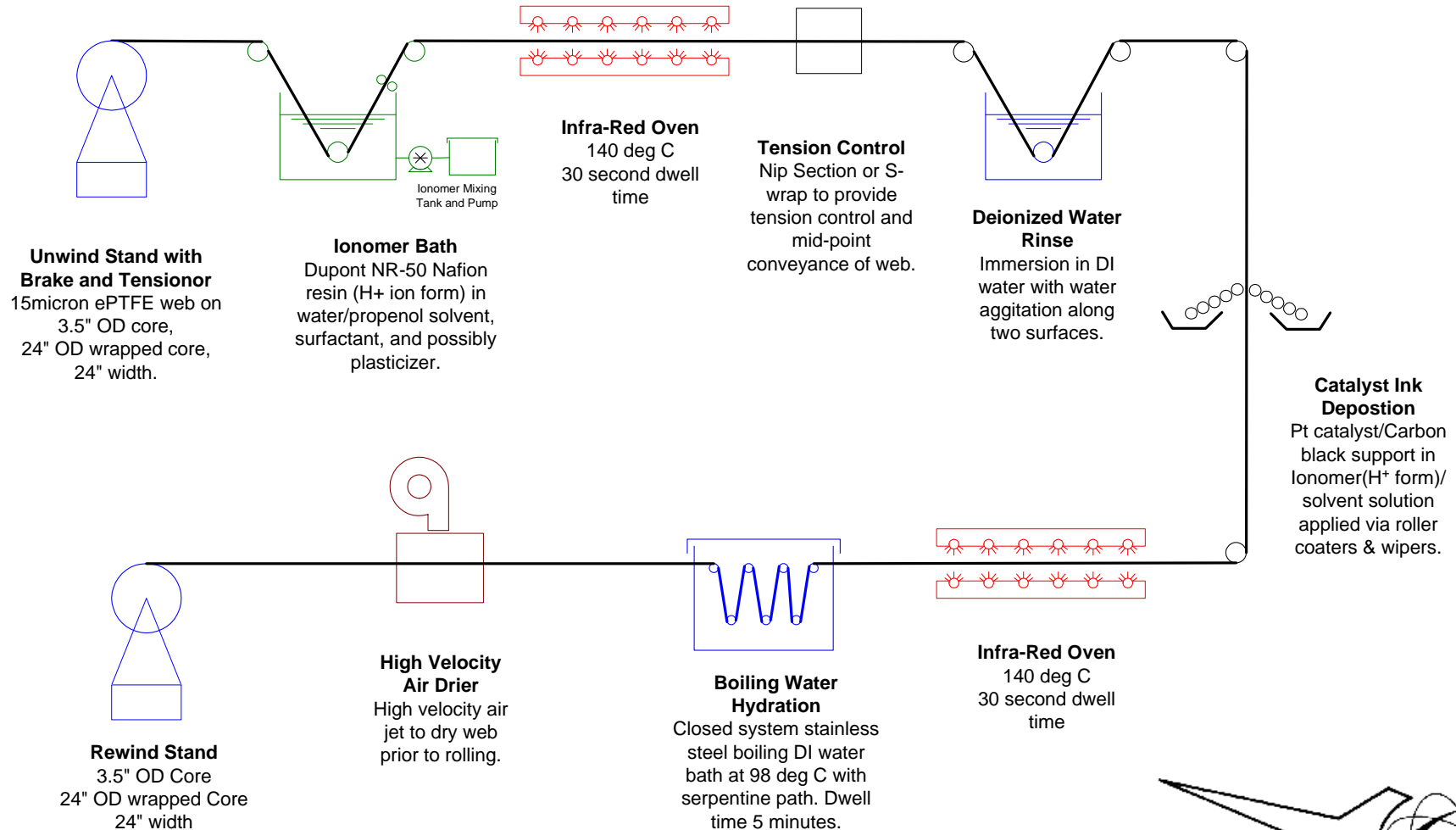
Source: "Detailed Manufacturing Cost Estimates for Polymer Electrolyte Membrane (PEM) Fuel Cells for Light Duty Vehicles", October 1997, F.D. Lomax, Jr., et al.

Available at WWW.DirectedTechnologies.com



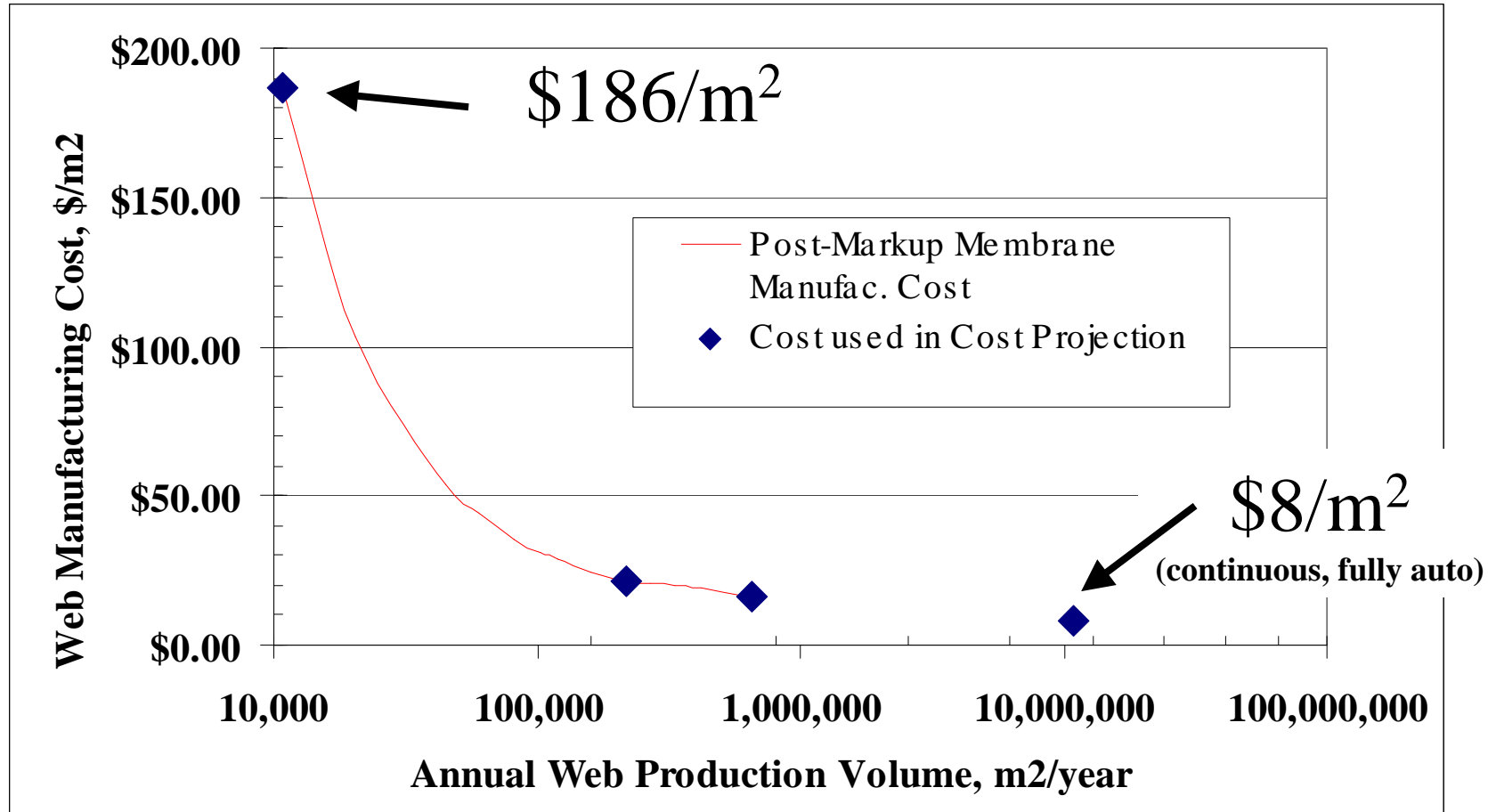
Baseline Low Production Rate Membrane Process Line

(Based on Gore-like approach)



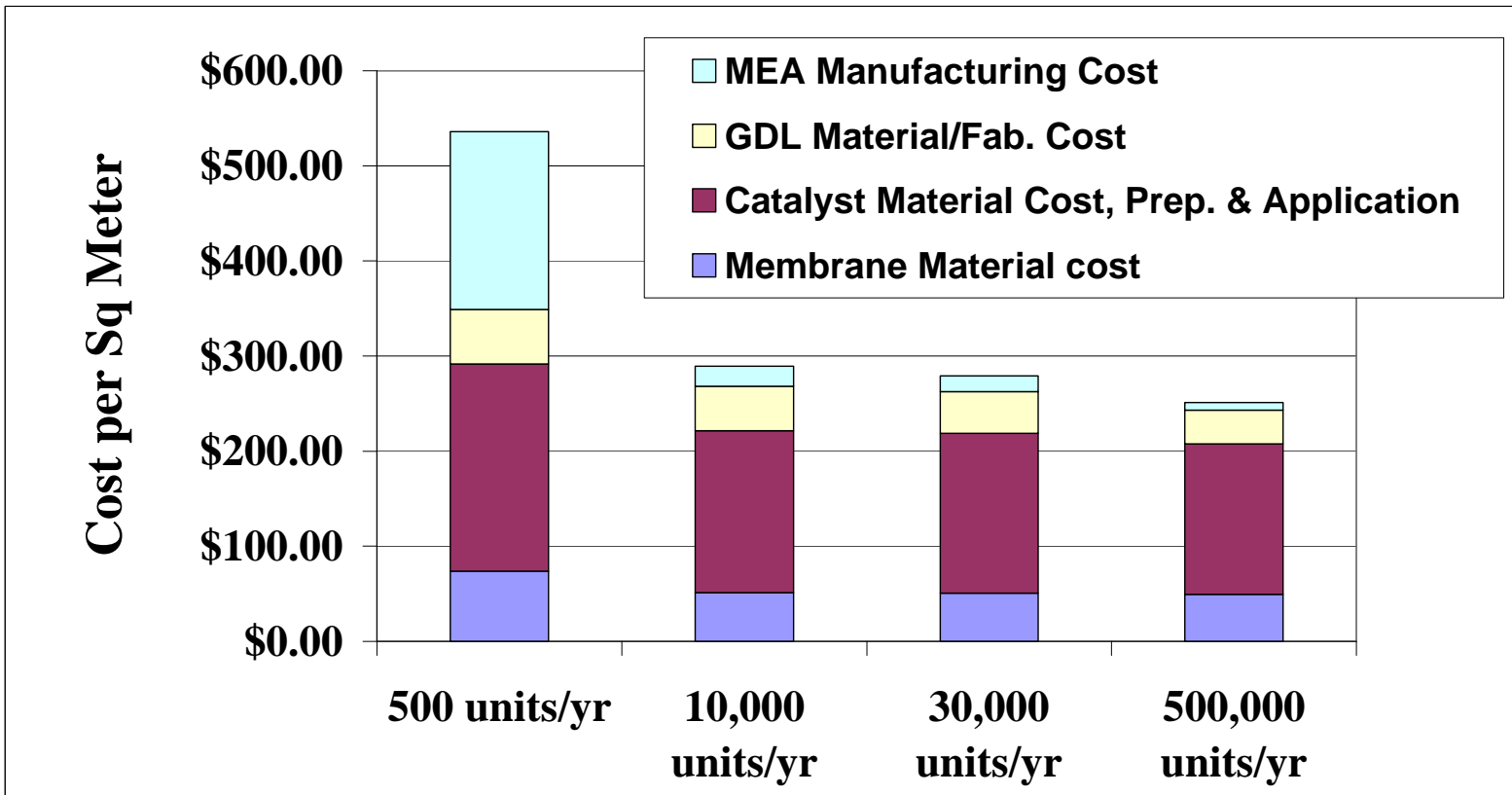
Manufacturing Cost of MEA

Semi-Continuous, Automated Process Train
(Includes markup but not materials, gasket, hot pressing)



Total Catalyzed MEA Cost

(not in frame, 0.7mg Pt/cm², 0.2mg Ru/cm²)



File: Stationary FC Cost adapted for Argonne DFMA.xls, Argonne Membrane Material Cost

- Membrane only quote from DuPont is \$450/m² in quantities >500 m² (25 units).

Stack Cost Summary, continued

(for set of 4 stacks, 0.7 v/c on reformate)

System Annual Production Rate	Stack Cost Alone: Does NOT include ancillary systems			
	500	10,000	30,000	500,000
Bipolar Plates				
Cathode Plate	\$696	\$531	\$513	\$497
Anode Plate	\$696	\$531	\$513	\$497
MEA				
Membrane Materials & Fabrication	\$5,628	\$1,568	\$1,449	\$1,236
Catalyst, Preparation & Application	\$4,709	\$3,681	\$3,634	\$3,421
Gas Diffusion Layer Material & Fabrication	\$1,243	\$744	\$686	\$669
MEA Gasket Material & Fabrication	\$97	\$68	\$68	\$61
MEA Hot pressing	\$468	\$173	\$154	\$144
Current Collectors	\$57	\$29	\$28	\$25
Insulators	\$35	\$8	\$7	\$6
Endplates	\$184	\$73	\$66	\$58
Tie-Rods	\$36	\$32	\$30	\$22
Stack Assembly	\$124	\$56	\$55	\$54
Stack Inspection/Leak Check	\$30	\$20	\$20	\$20
10% Cost Provision	\$1,400	\$751	\$722	\$671
Total Stack Cost	\$15,405	\$8,266	\$7,944	\$7,380
Total Stack \$/kW_{gross} (based on 55kW_{gross})	\$280/kW_{gr}	\$150/kW_{gr}	\$144/kW_{gr}	\$134/kW_{gr}



Ancillary Components/Subsystem Cost Summary

Subsystem	Item #	Item	Annual Complete Unit Production Rate			
			500/year	10,000/year	30,000/year	500,000/year
Coolant Loop			\$619.94	\$486.33	\$450.12	\$372.75
	1	Coolant Pump & Electric Motor	\$135.63	\$104.36	\$101.89	\$94.88
	2	Coolant Pump Controller	\$30.14	\$27.83	\$27.17	\$25.30
	3	Radiator Assembly	\$333.61	\$267.86	\$249.06	\$185.53
	4	Coolant Reservoir	\$22.61	\$13.92	\$10.87	\$10.12
	5	Coolant Thermostat	\$22.61	\$16.70	\$13.59	\$12.65
	6	Coolant bypass valve	\$75.35	\$55.66	\$47.55	\$44.28
Fuel Loop			\$879.24	\$616.03	\$572.78	\$450.13
	7	Fuel tank Subsystem				
	8	Fuel tank & assoc. hardware	\$256.19	\$136.61	\$127.02	\$107.53
	9	Submersible HP fuel pump	\$474.71	\$365.27	\$339.63	\$263.54
	10	High Pressure Fuel injector	\$148.35	\$114.15	\$106.13	\$79.06
Water Loop			\$1,209.08	\$910.87	\$831.91	\$638.61
	11	Water Reservoir	\$15.07	\$11.13	\$9.51	\$7.59
	13	Vortex Water knock-out drum	\$45.21	\$27.83	\$24.45	\$18.98
	14	Sump pump-Vortex Water Knock-Out	\$22.61	\$18.09	\$13.59	\$10.12
	15	Sump pump-Reformate Condensor	\$45.21	\$27.83	\$24.45	\$18.98
	16	High Pressure Water Rail System				
	17	High pressure water pump	\$474.71	\$365.27	\$339.63	\$263.54
	18	Pressure regulator	\$75.35	\$55.66	\$47.55	\$44.28
	19	High pressure rail line	\$37.68	\$20.87	\$16.30	\$12.65
	20	High Pressure water injector (reactor)	\$296.69	\$228.29	\$212.27	\$158.13
	21	High pressure water injector (air humidifier)	\$148.35	\$114.15	\$106.13	\$79.06
	22	Water Deionizing filter	\$48.22	\$41.75	\$38.04	\$25.30

Ancillary Components/Subsystem Cost Summary, continued

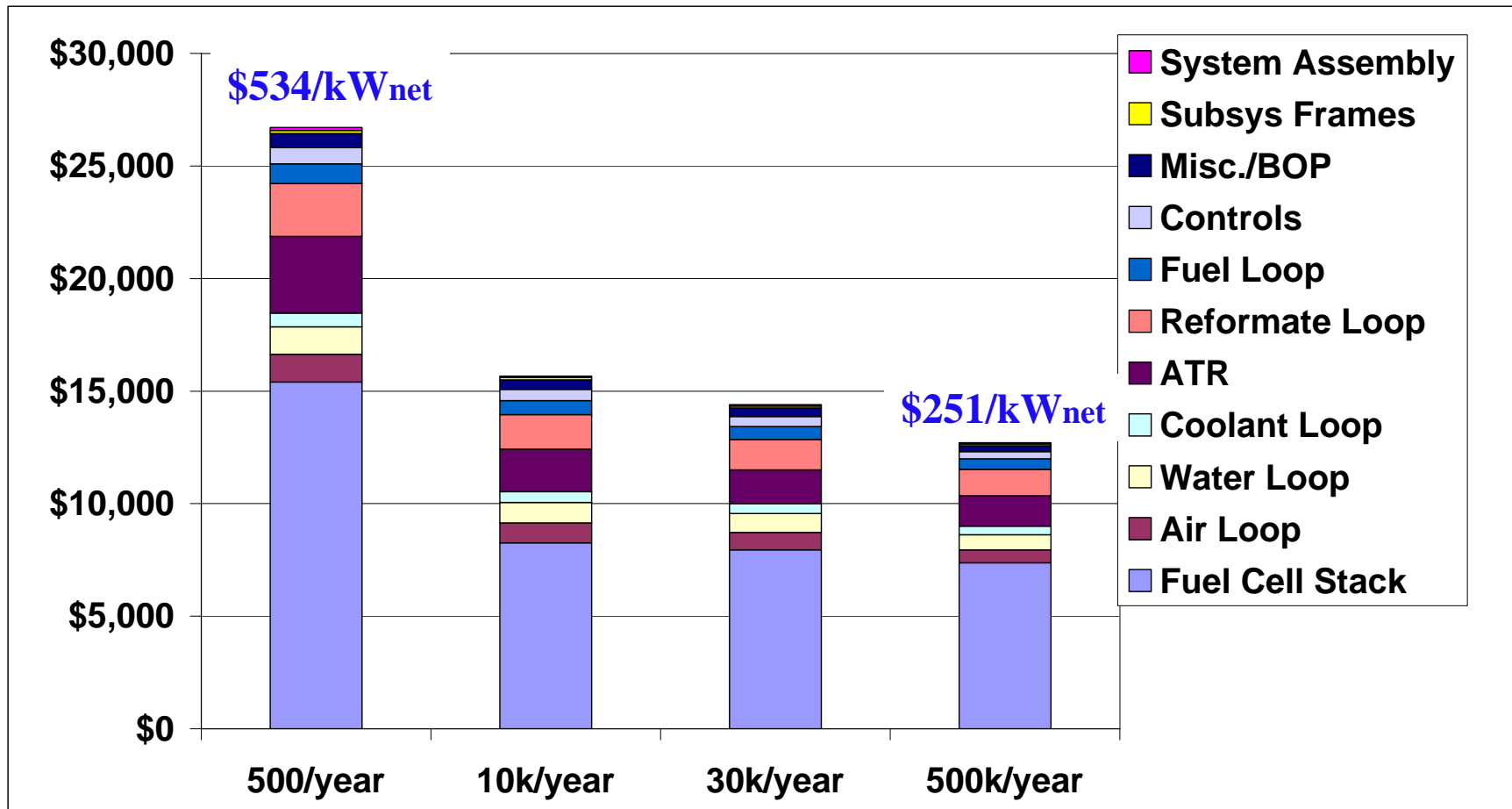
Air Loop			\$1,160.39	\$820.99	\$733.59	\$511.06
	23	Compressor/Motor/Expander Unit (CMEU)	\$489.78	\$347.88	\$326.04	\$253.00
	23a	Air filter				
	24	Air Mass Flow Sensor-Reformer Air Supply	\$52.75	\$41.75	\$33.96	\$27.83
	25	Air Throttle Body	\$414.43	\$313.09	\$271.70	\$158.13
	26	Air Mass Flow Sensor-Fuel Cell Air Supply	\$52.75	\$41.75	\$33.96	\$27.83
	34	Air humidifier	\$150.70	\$76.53	\$67.93	\$44.28
ATR	27	ATR Reactor Subsystem	\$3,393.63	\$1,877.84	\$1,501.91	\$1,347.13
Reformate Loop			\$1,258.24	\$811.47	\$705.04	\$611.10
	28	PROX Unit	\$504.74	\$227.04	\$195.60	\$174.67
	29	PROX air control solenoid	\$150.70	\$111.32	\$101.89	\$82.23
	30	Water Thermostat	\$75.35	\$55.66	\$47.55	\$44.28
	30a	Proportional bypass valve				
	31	Catalytic burner	\$301.40	\$250.47	\$217.36	\$189.75
	32	Reformate Condensor	\$150.70	\$111.32	\$95.10	\$75.90
	32a	Reformate bypass valve	\$75.35	\$55.66	\$47.55	\$44.28
Fuel Cell Stack			\$15,404.97	\$8,265.79	\$7,944.19	\$7,380.40
	33	Fuel Cell ISP				
Controls			\$718.84	\$500.94	\$441.51	\$305.71
	34	Electronic Engine Controller	\$379.76	\$292.22	\$271.70	\$210.83
	35	Controls fuel injector				
	36	Controls reactor water metering				
	37	Reformer Control System				
	38	HP fuel pump				
	39	CO sensor	\$339.08	\$208.73	\$169.81	\$94.88
Miscellaneous/Balance of Plant			\$632.94	\$431.37	\$387.17	\$253.00
	40	Startup battery	\$30.14	\$27.83	\$27.17	\$25.30
	41	Electrical	\$301.40	\$208.73	\$183.40	\$101.20
	42	System mounting	\$150.70	\$97.41	\$88.30	\$63.25
	43	Water, coolant, gas lines	\$150.70	\$97.41	\$88.30	\$63.25

File: BOM V3.1.xls, System BOM



System Cost Summary

(50kW_{net} Reformer/FC System at 0.7v/cell)



File: BOM v3.1xls, System BOM



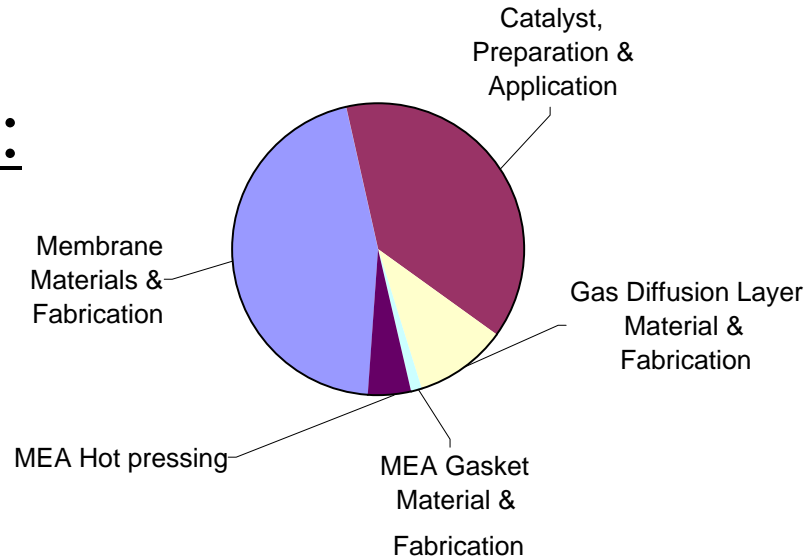
Stack Cost Summary

0.7v/c Reformate stacks (set of 4)

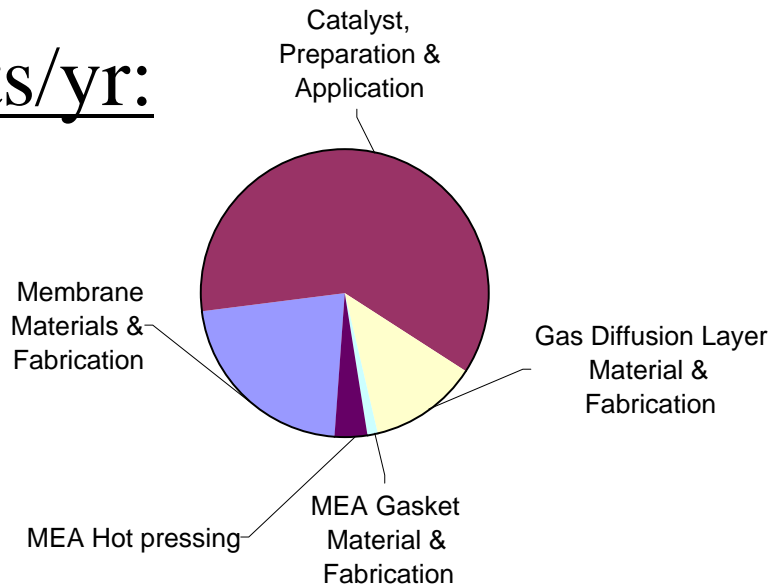


Reformat System MEA

500 Units/yr:



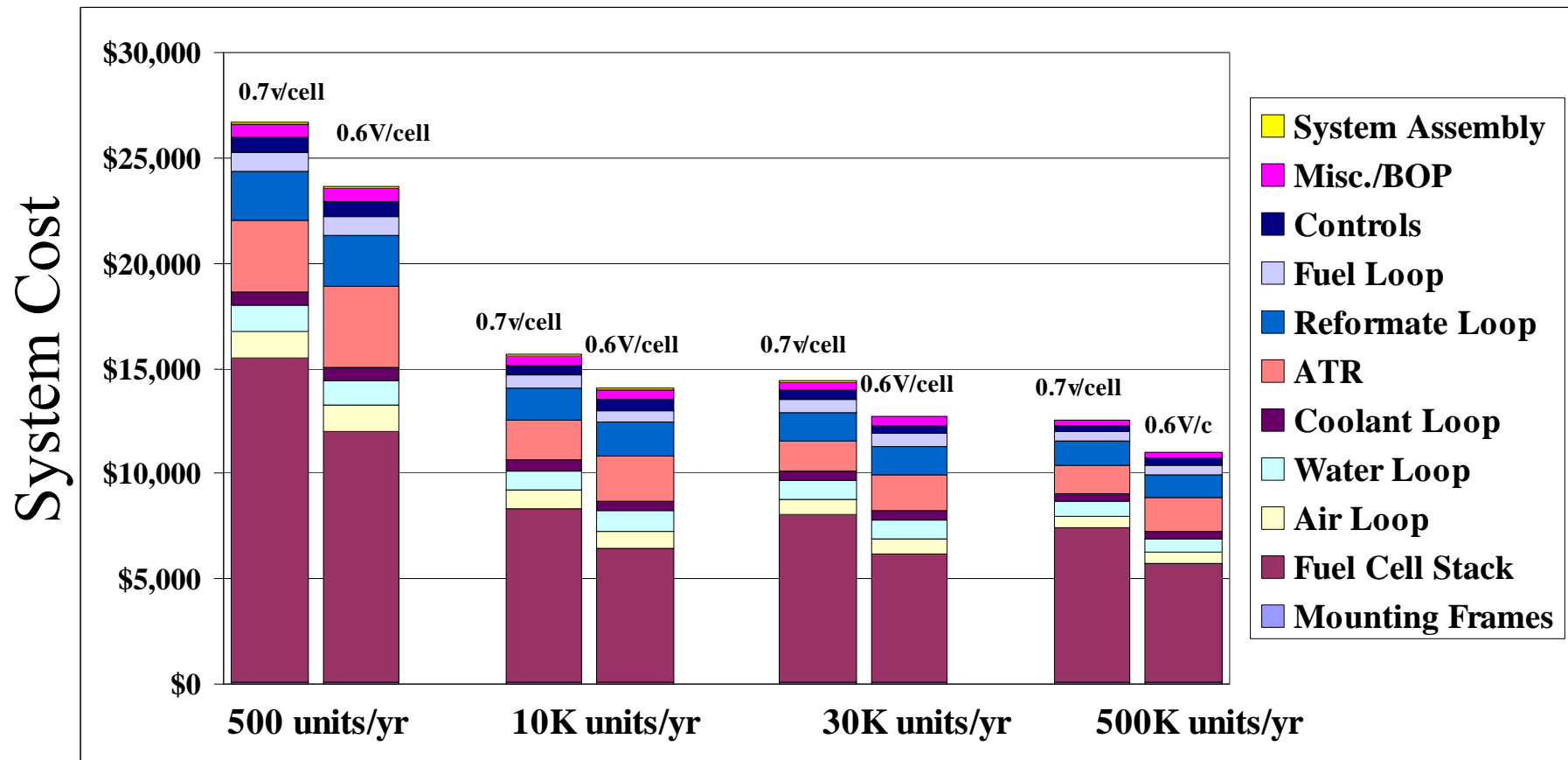
500k Units/yr:



**Catalyst and
Ionomer costs
are key.**

Reformat System Comparison

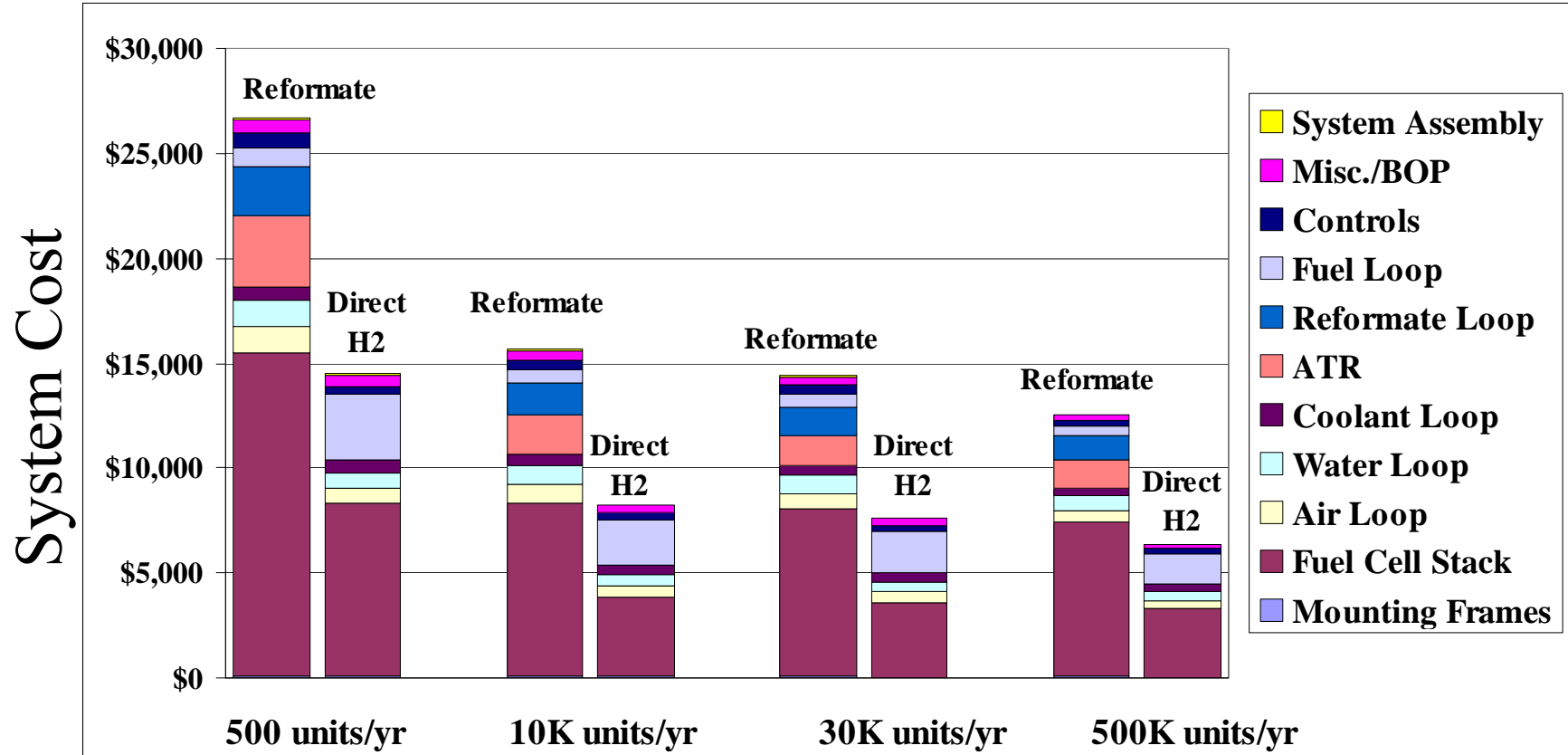
0.7v/cell vs. 0.6v/cell



System Comparison

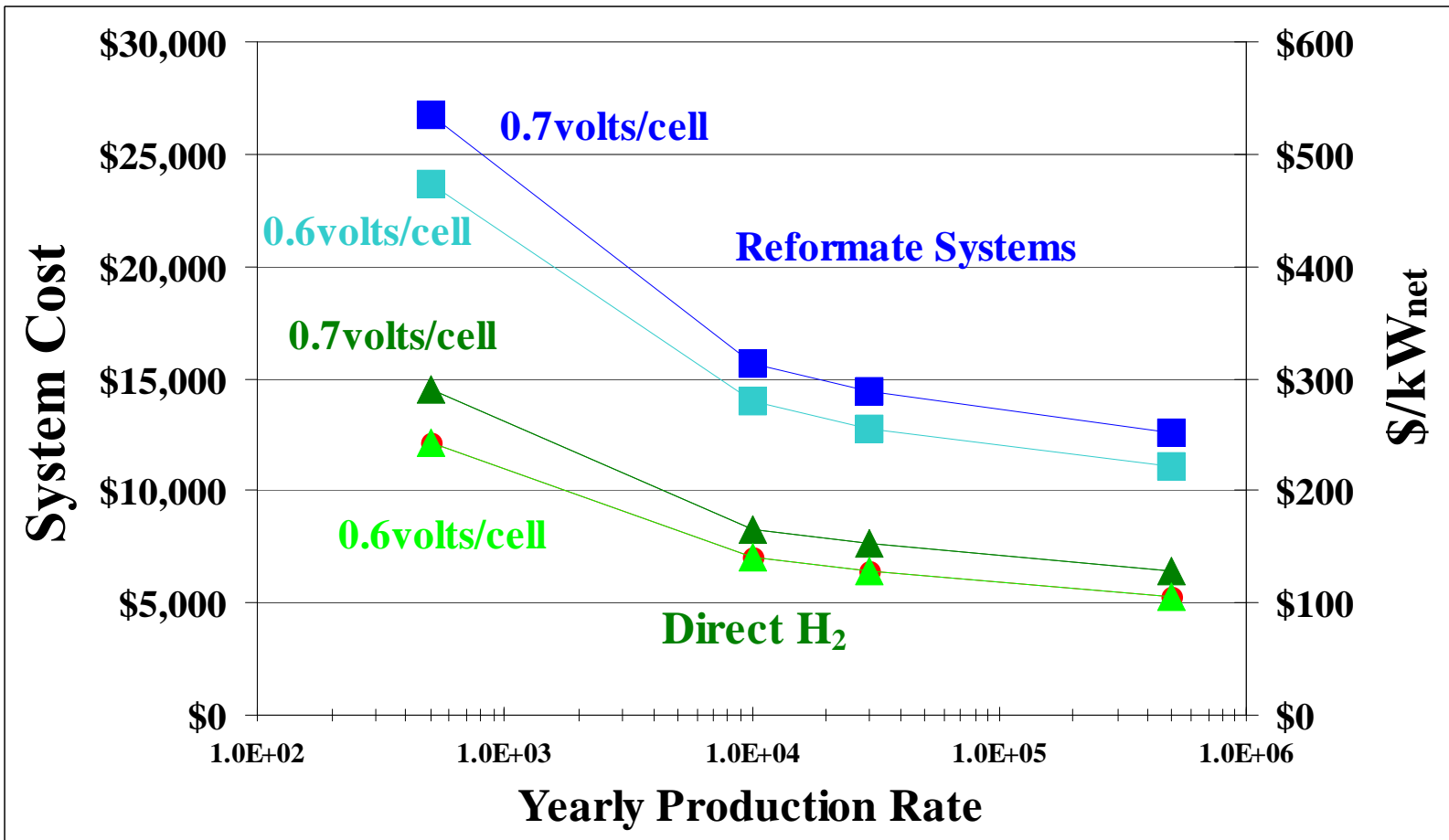
Reformat System vs. Direct H2 System

(both at 0.7volts/cell)



System Comparison

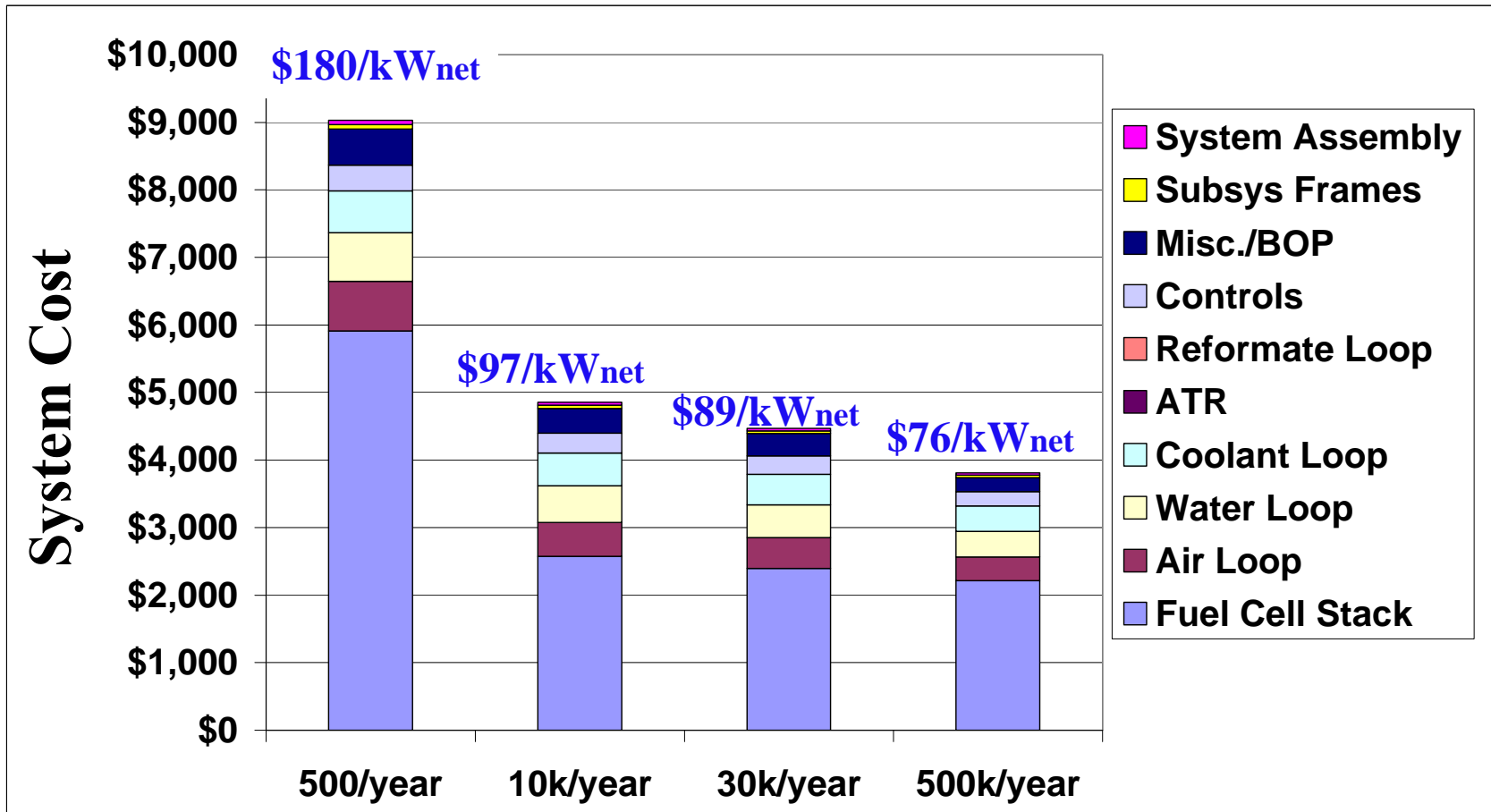
Reformate vs. Direct H₂



Both systems include fuel supply.

Direct H₂ Fuel Cell Stack & Peripherals

0.6v/cell, No H₂ Storage System



File: BOM v3.1.xls, System BOM

System Efficiency

	2001 DOE Goal	Reformer Systems		Direct H2 Systems	
Cell Voltage		0.6	0.7	0.6	0.7
Fuel Cell Stack Eff.*	44.0%	35.1%	41.5%	43.1%	51.1%
Reformer Eff.**	75.0%	80.5%	80.5%	NA	NA
System Net Efficiency***	33.0%	28.2%	33.4%	43.1%	51.1%

* FC Stack Efficiency = Net Elect. Power/ Reformer Outlet LHV

**Reformer Efficiency = Reformer Outlet LHV/Fuel Inlet LHV

*** System Efficiency = Net Elect. Power/ Fuel Inlet LHV

Summary & Conclusions

• Reformate Systems

- Fuel cell stack dominates total system cost (~50% of total system) because of low power density on reformate.
- MEA cost dominates stack costs due to high catalyst /ionomer/GDL costs
- Reactor & Peripherals add (only) \$3,000 ($\$60/\text{kW}_{\text{net}}$) to \$6,500 ($\$130/\text{kW}_{\text{net}}$)
- Overall System cost is high:
 - \$13K ($\$251/\text{kW}_{\text{net}}$) to \$27K ($\$534/\text{kW}_{\text{net}}$) depending on production rate.

• Direct H₂ Systems

- Much higher power density than reformate systems, lower catalyst loading, less membrane used
- Stack still about 50% of total system cost
- Results in lower system cost:
 - \$5.2K ($\$105/\text{kW}_{\text{net}}$) to \$12K ($\$243/\text{kW}_{\text{net}}$) depending on production rate.
- Fuel Cell Stack & Peripherals cost (excluding H₂ storage): \$76-\$180/ kW_{net}