Conceptual Design of POX / SOFC 5kW net System

Final Report
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The final report is divided into five sections with a detailed appendix.

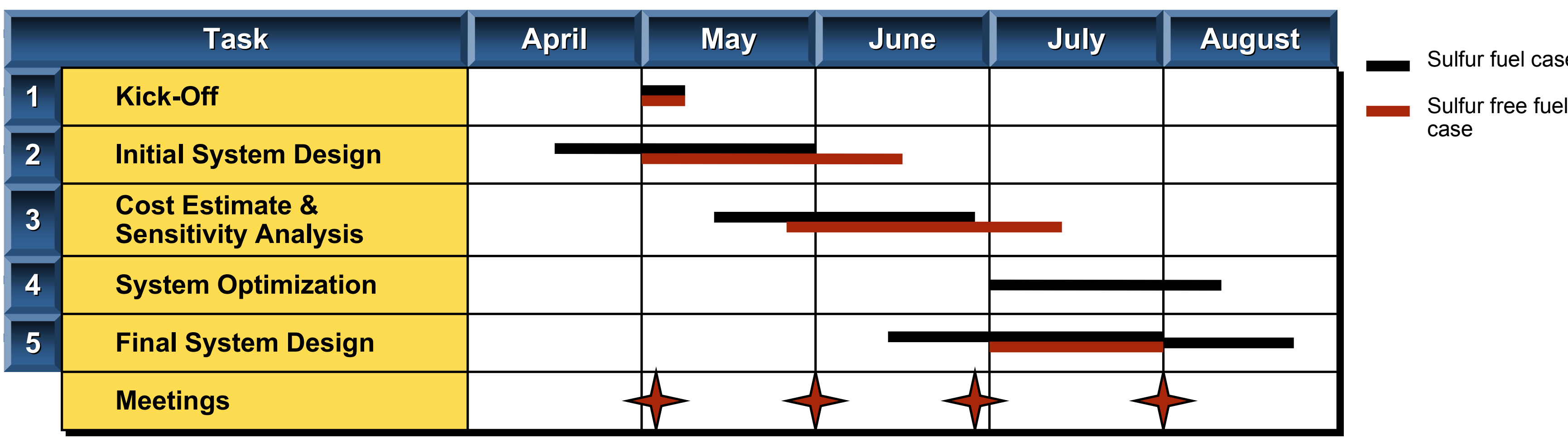
Advances in SOFC technology now appear to enable broad small-scale applications in both stationary and transportation markets.

- Planar, thin electrolyte, electrode-supported configuration improves performance significantly
  - Increases in power density (~500 mW/cm^2 or greater)
  - Lower operating temperatures (650-850°C)
  - Lower cost metallic separator plates
  - Elimination of very high temperature molten glass seals
  - Potential for higher stack efficiency
  - Reduced heat losses from lower operating temperature
- Potential for economy of scale for manufacturing
  - Geometry lends itself to high volume, low cost manufacturing techniques
  - Broad applicability is consistent with high-volume manufacturing

Effective system design and integration has not yet received sufficient attention and is critical for the development of competitive products.

The project was organized into five tasks; using two cases of fuel, sulfur-containing gasoline and sulfur-free Fisher-Tropsch Diesel.

Task 1	Task 2	Task 3	Task 4	Task 5
Kickoff	**Initial System Design**	**Cost Estimate & Sensitivity Analysis**	**System Optimization**	**Final System Design**
◆ Confirm design specs ◆ Agree on stack parameters ◆ Review initial design	◆ Thermodynamic system model ◆ Size components ◆ Layout of components	◆ Cost BOP components ◆ Estimate system cost ◆ Perform sensitivity analyses (cost, performance)	◆ Support CMU in Multi-Objective Optimization	◆ Finalize system designs

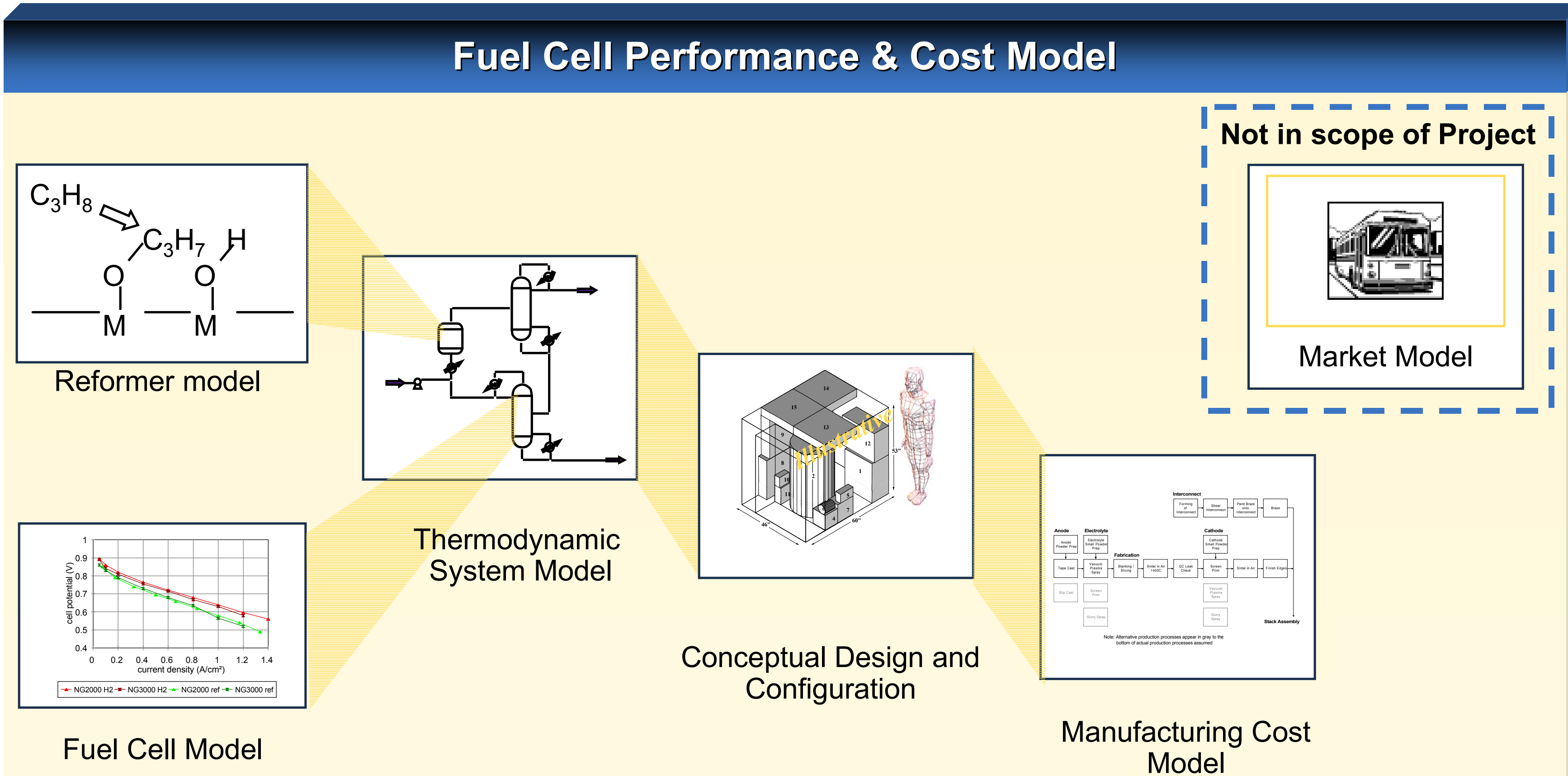


The objective of this project was to develop a conceptual design package and cost estimate for a planar anode supported SOFC system.

System Performance	System Physical Characteristics	System Cost Targets
◆ Efficiency greater than 35% peak power (DC/LHV) ◆ Rating, 5 kW net ◆ Operating life greater than 5000 hours ◆ Cold (25°C) start-up time less than 10 minutes ◆ Voltage – 42 VDC ◆ No external water supply needed	◆ Volume goal less than 50 liter ◆ Mass goal less than 50 kg ◆ Operating temperature 800°C ◆ Surface temperature of system package less than 45°C	◆ Cost of balance of plant goal less than $400/kW ◆ Ultimate goal $400/kW for system

The target application for this module is an auxiliary power unit (APU) for on-road vehicles such as trucks.

We used our multi-level RaPID™ development methodology to design a POX/SOFC system for auxiliary power unit (APU) applications.



We used thermodynamic models coupled with detailed manufacturing cost models to identify the key design and cost drivers for planar technology.

Stack thermal management and power density are critical issues impacting the cost and performance of reformer/planar SOFC systems.

How can reformer / planar SOFC systems be applied to truck APUs and how much will they cost?

	System Performance[1]	Cost	Volume & Weight
Internal Stack Thermal Management[2]	●	●	●
Power density / Operating Voltage	●	●	●
Stack Fuel Utilization	●	◒	◒
Stack Thermal Mass[3]	●	○	○
Recuperator	○	●	●
Parasitic power	◒	●	●
Reformer efficiency	◒	◒	◒
Insulation	○	○	●

● Critical ◒ Important ○ Not Leveraging

1. System performance refers to e.g. system efficiency, start-up and shut-down time.
2. Stack thermal management refers to the maximum thermal gradients allowable and degree of internal reforming possible at anode.
3. Critical if provisions must be made to meet tight start-up specifications.

Stack thermal management directly impacts recuperator and parasitic requirements and system volume.

Individual components have been distributed among the major sub-systems.

Reformer	Fuel Cell	Recuperators	Balance-of-Plant
◆ Homogeneous gas phase POX reformer[1] ➢ POX air preheater ➢ Air, fuel, recycle mixer ➢ Eductor ➢ Primary cathode air preheater ◆ ZnO sorbent bed	◆ Fuel Cell Stack (Unit Cells) [3] ◆ Balance of Stack[4]	◆ Anode recuperator ◆ Tailgas burner[2] ➢ Fuel vaporizer ◆ Secondary cathode air preheater	◆ Startup power ➢ Start-up battery ➢ Blower for active cooling ➢ Switching regulator for recharging ◆ Control & electrical system ➢ System sensors ➢ Controls ➢ System logic ➢ Safety contactor ◆ Rotating equipment ➢ Air Compressor ➢ Fuel Pump ◆ System insulation ◆ System piping

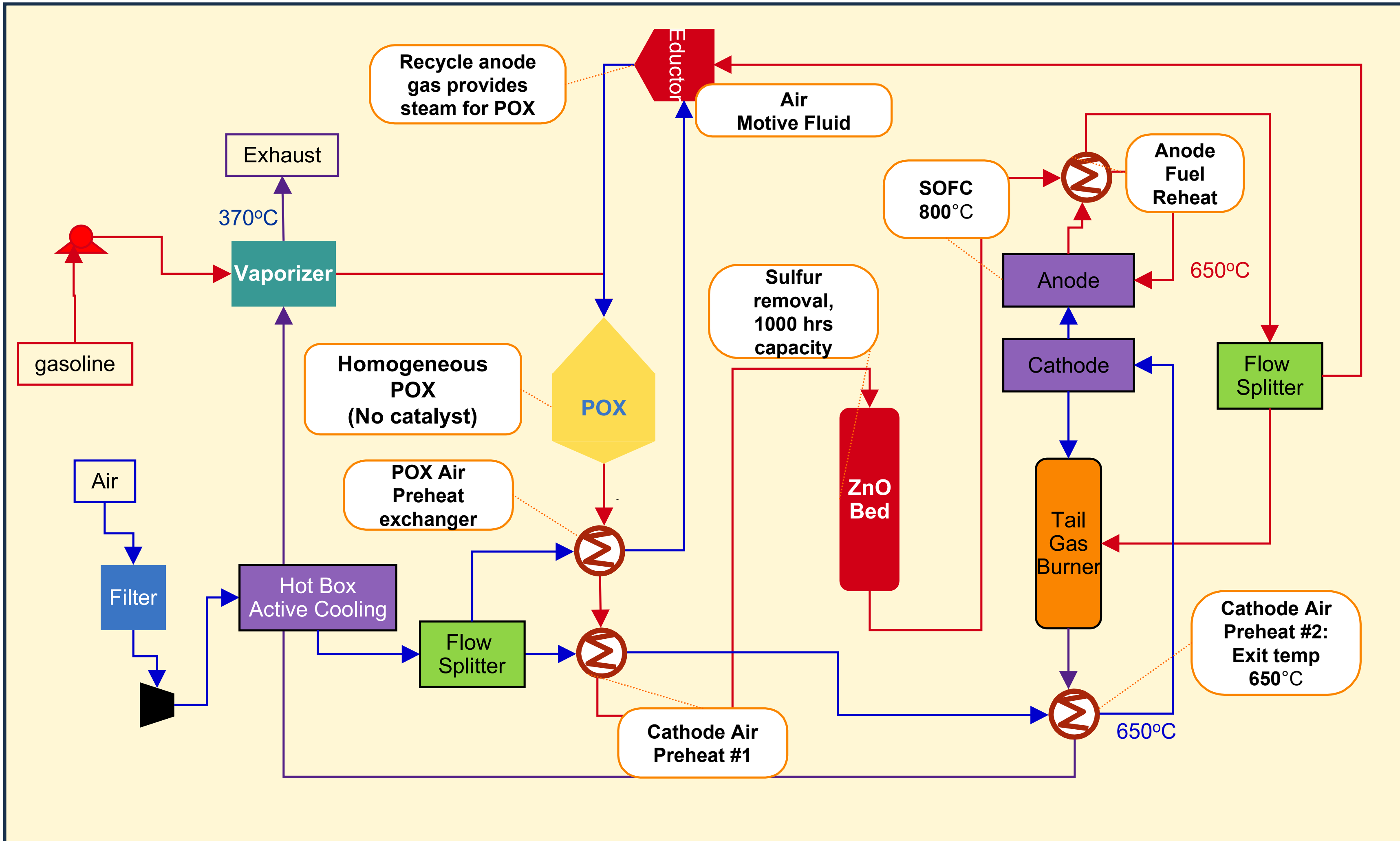
1. The reformer also incorporates the POX air preheater, primary cathode air preheater, air/fuel/recycle mixer, and eductor integrated inside.
2. The Tailgas burner incorporates the fuel vaporizer, and in case 2 the secondary cathode air preheater integrated inside.
3. The fuel cell stack includes cathode, anode, electrolyte, interconnects, and layer assembly, and stack assembly
4. The balance of stack includes endplates, current collector, electrical insulator, outer wrap, and tie bolts. It is assumed that the stack is internally manifolded.

Five separate cases were modeled to investigate the effects of different operating conditions and fuel type.

	Base Case	Case 1 Improved Stack Design	Case 2 Poorer Stack Operation	Case 3 Higher Power Density	Case 4 Sulfur-free Fuel
Cathode Air Inlet Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Anode fuel Utilization	90%	90%	70%	90%	90%
Fuel	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	0 ppm S Diesel
Power density, W/cm^2	0.3	0.6	0.3	0.6	0.3

NOTES.
1. Case 3 has the same performance (efficiency) as the base case except that the fuel cell stack operates with a higher power density (0.6 W/cm^2 compared with 0.3 W/cm^2).
2. Case 4 has the same power density as the base case except that the fuel is sulfur-free Fischer-Tropsch Diesel.

The SOFC system flow diagram shows that equipment for heat removal (and recovery) and fluid movement plays a critical role in the system.



System efficiency targets of 35 percent can be met with sufficient stack thermal management[5].

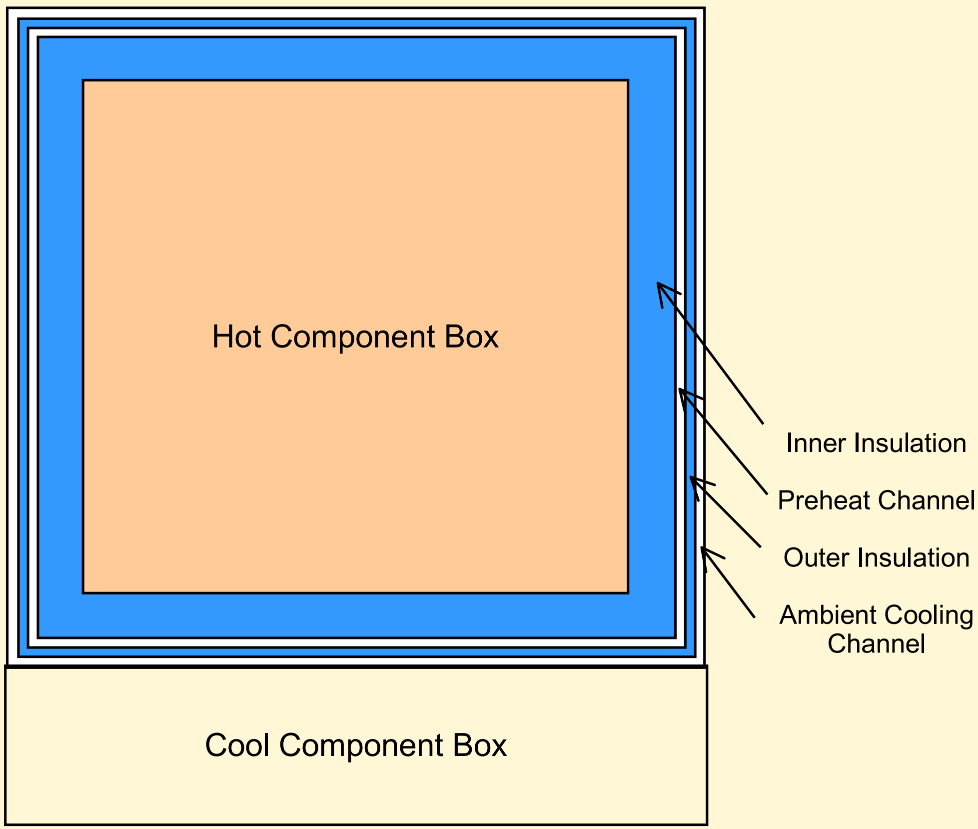
	Base Case	Case 1	Case 2	Case 3	Case 4
Anode Fuel Utilization	90%	90%	70%	90%	90%
Fuel Cell Efficiency[3]	49%	49%	38%	49%	49%
POX Effluent Temperature	890ºC	890ºC	940ºC	890ºC	910ºC
Estimated POX (with recycle) Efficiency[1]	87%	87%	91%	87%	87%
Cathode Inlet Air Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Required Cathode Excess Air	760%	330%	1,100%	760%	750%
Required Compressor Pressure[2]	1.28 atm	1.19 atm	1.39 atm	1.28 atm	1.29 atm
Parasitic Loads	**750 W**	**260 W**	**1,700 W**	**750 W**	**770 W**
Exhaust Temperature	370ºC	590ºC	370ºC	370ºC	380ºC
Resultant Overall Efficiency[4]	**37%**	**40%**	**26%**	**37%**	**37%**
Required Fuel Cell gross power rating, kW	**5.75**	**5.26**	**6.70**	**5.75**	**5.77**

1. LHV of the POX outlet stream divided by the LHV of the fuel inlet stream not including the anode recycle inlet. Does not include internal fuel cell reforming.
2. Required pressure to overcome air side pressure drops. Slightly different tube diameters and geometries were used in each case to keep the pressure requirement as low as possible without incurring large volume increases.
3. Fuel cell efficiency is defined as the product of the fuel utilization, voltage (electrical) efficiency and thermodynamic efficiency. Fuel cell efficiency is equal to (Fuel utilization) * (operational voltage/open cell voltage) * (ΔG_{rxn}/LHV fuel). Assume an open cell voltage of 1.2 volts for all anode reactions.
4. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)
5. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power. Thermal management of the stack refers to the maximum allowable temperature gradients allowable in the stack due to thermal stress. Thermal management also encompasses the amount of fuel that can be internally reformed at the anode which can serve to regulate the temperature in the stack.

The system is divided into a hot component box with active air cooling to decrease insulation requirements, and a cool components box.

NETL SOFC System Layout

Note: NOT TO SCALE.



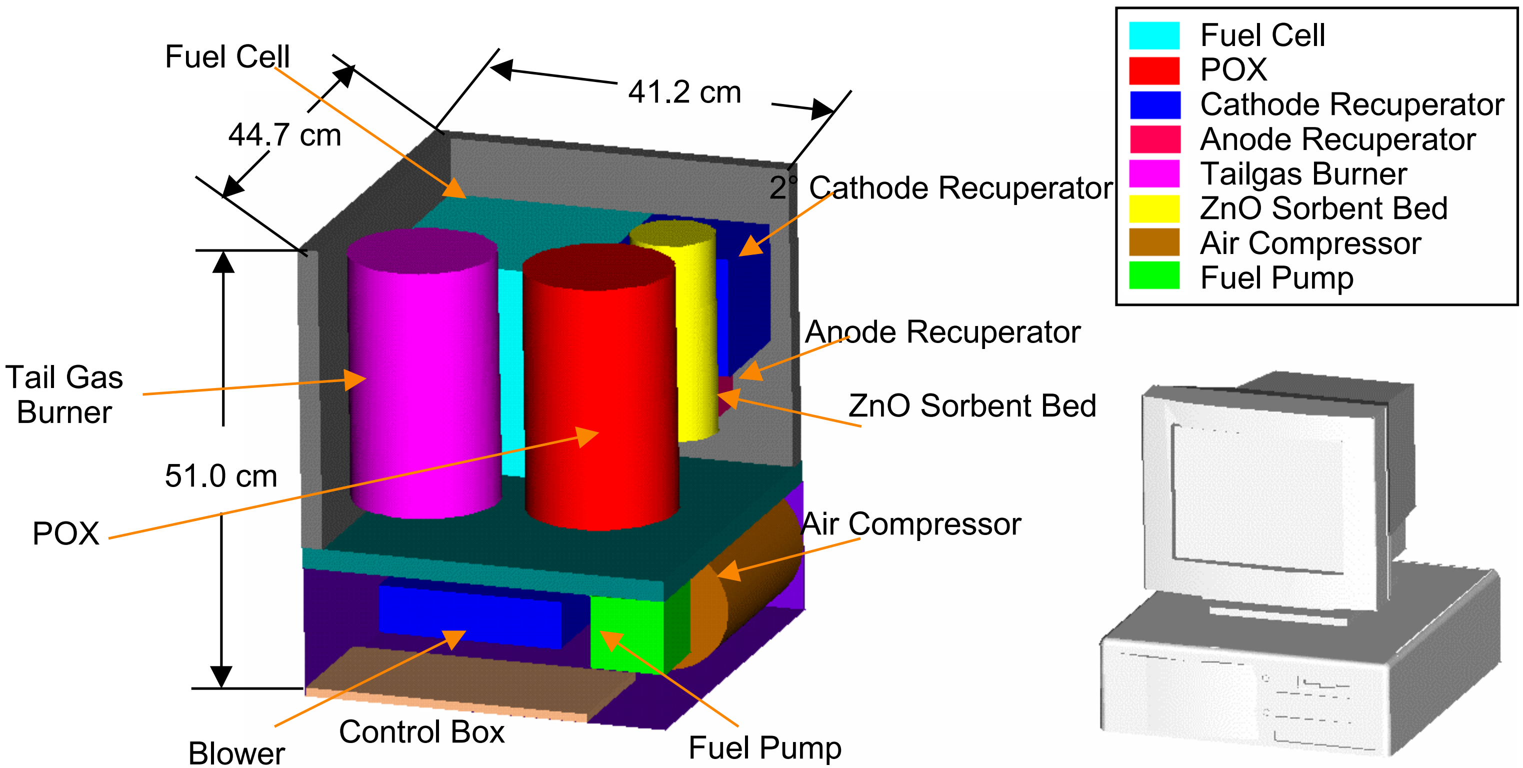
Hot Component Box:

- Fuel cell stack
- POX reformer
- Anode fuel heat exchanger
- Tailgas burner
- ZnO bed (sulfur removal)
- Recuperator heat exchangers
- Eductor

Cool Component Box

- Control system
- Air compressor and filter
- Fuel pump and filter
- Air blower for active cooling
- System battery

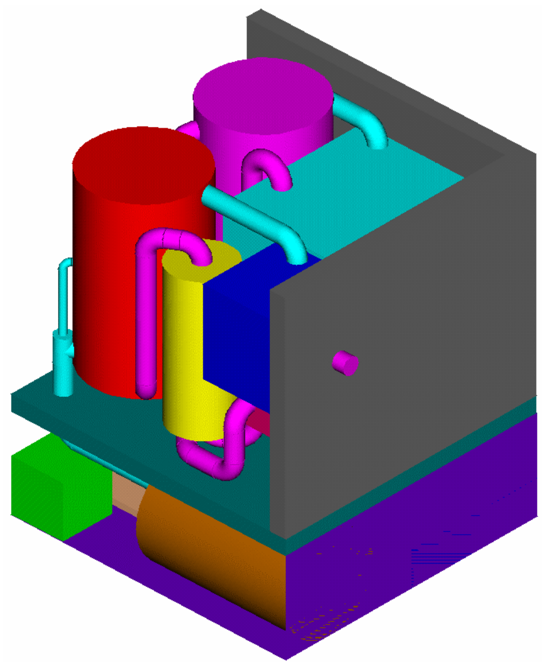
In the first generation configuration, the hot component box and the cool component box have the same footprint.

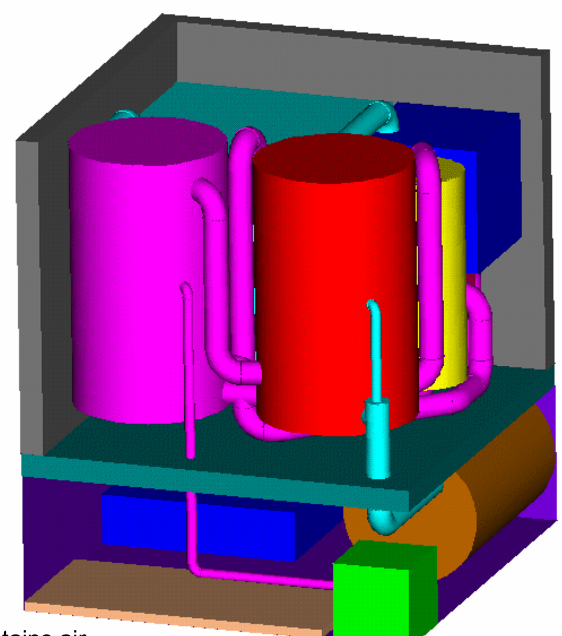


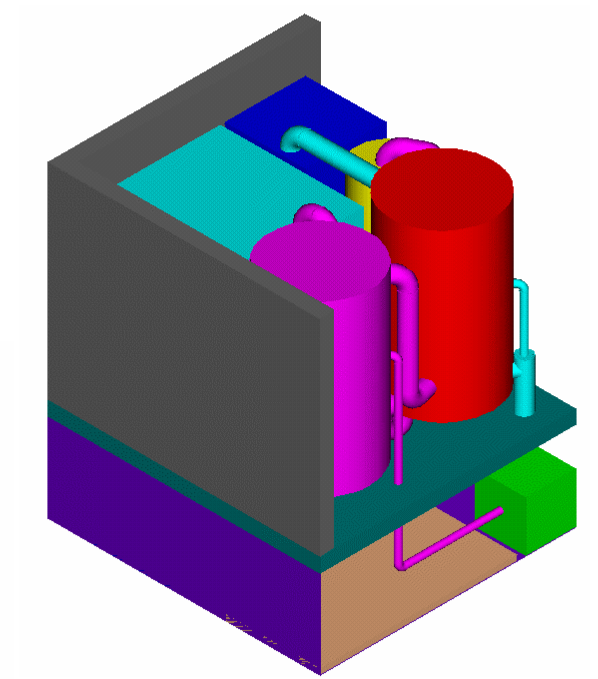
System package volume 94 liters

Comparison for Scale

While the packaging of the first generation configuration is carefully designed, some further space savings in packaging are likely to be feasible.

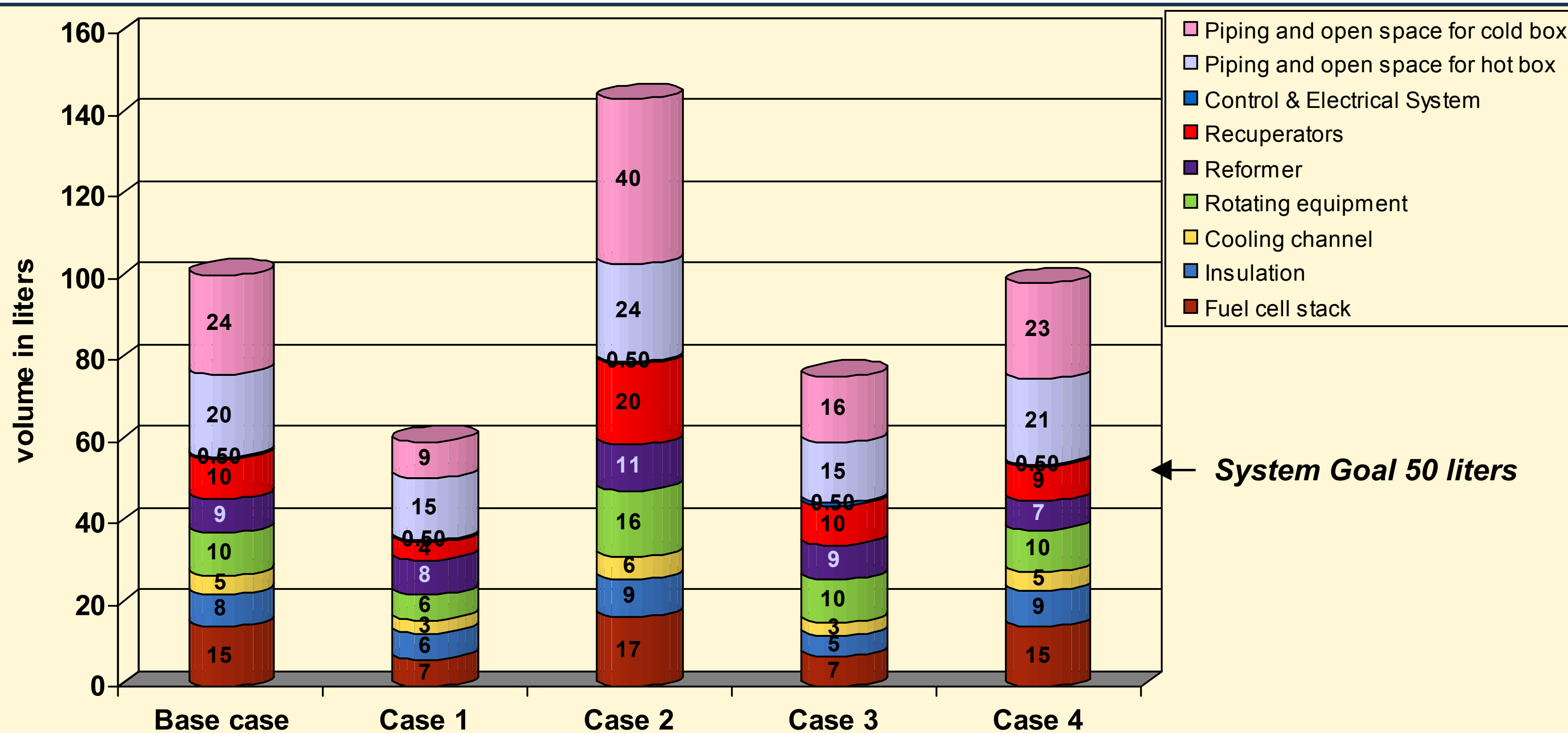






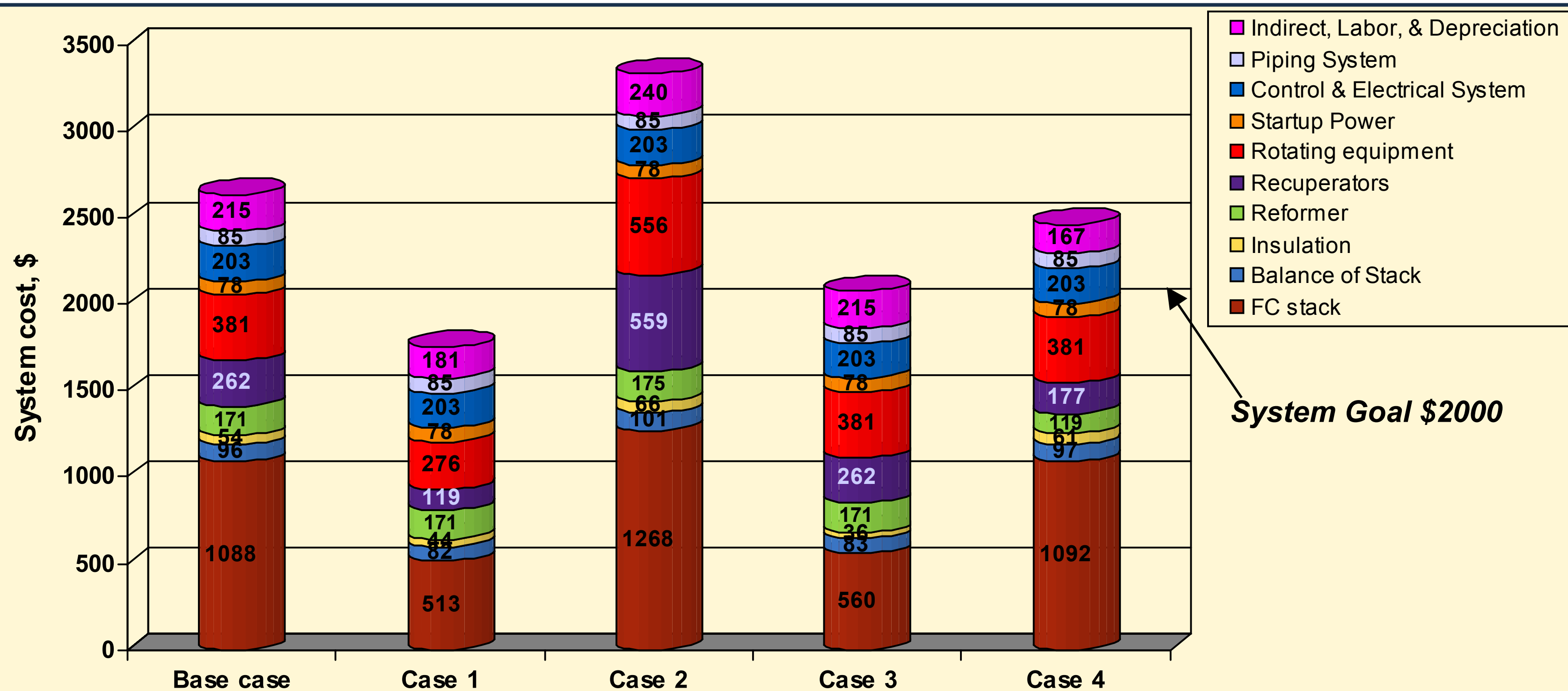
Note:
Pink manifolding contains fuel. Blue manifolding contains air.
The layout shown is for a first generation layout typically for a proof of system prototype. Commercial systems will likely incorporate further component integration.

Sufficient stack power density and thermal management are required to approach the volume target of 50 liters (results were 60 to 145 liters).



Notes:
1. The fuel cell stack line items does not include insulation or external manifolding.
2. The system insulation includes high and low temperature insulation
3. The reformer includes volume for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
4. The recuperators include the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
5. Rotating equipment includes the air compressor, fuel pump, and air blower for active cooling
6. The anode preheater and the secondary cathode air exchanger are configured as compact finned cross flow cube heat exchangers
7. In the base case, assuming all the volume of manifolding is in the hot box, the 20 liters includes 14.6 liters of piping for 5.4 liters of open space in the base case hot box.
8. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.
9. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power.

Target system costs appear achievable with high power density; the fuel cell stack cost represents 27 to 44% of the system cost.



Notes:
1. The fuel cell stack cost does not include protective conductive coatings on the metallic interconnect, which if needed, could increase stack costs by 5-10%.
2. The fuel cell stack line items does not include insulation or external manifolding.
3. The fuel cell stack balance includes end plates, current collector, electrical insulator, outer wrap, tie bolts, FC temperature sensor, and cathode air temperature sensor
4. The system insulation includes high and low temperature insulation and metal cost for manifolding of active cooling jacket
5. The reformer includes cost for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
6. The recuperator includes the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
7. Rotating equipment includes air compressor and fuel pump
8. Startup power includes cost for battery and active cooling blower
9. Indirect, Labor, and Depreciation includes all indirect costs, labor costs, and depreciation on equipment, tooling, and buildings
10. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

System efficiency targets can be met under most circumstances but heat-up time targets are unrealistic without further technology improvements.

- System efficiency of greater than 35% is easily achievable[1]:
  - Typical efficiency 37%
  - 40% efficiency appears achievable (even at this scale)
  - Stack thermal management can significantly impact efficiency
- Use of sulfur free fuel does not dramatically change system performance or cost from base case sulfur containing fuel operation
  - Alternative reforming technologies such as steam reforming or fully internal reforming were not considered
  - The sulfur free fuel case represents a conservative impact of possible sulfur-free alternative fuels
- A 10 minute start-up time appears unrealistic with current technology:
  - Thermal mass of stack would require significant additional heating and air movement capacity, with significant size (30%) and cost (15%) penalties
  - Materials thermal shock resistance issues will further increase start-up time
  - Minimum practical start-up times from a system perspective is about 30 minutes
  - Heat-up time will also be dependent upon sealing technology used for stack

1. The system efficiency was set by a using a 0.7 Volt unit cell voltage, a POX reformer, and required parasitics. Higher efficiency is achievable at higher cost by selecting a higher cell voltage

Our analysis indicates that achieving the 50-liter volume target will be challenging without further improvements in stack technology.

- System volume estimates range from 60 to 145 liters[1].
- The balance of plant represented by the reformer, recuperators, and rotating equipment represent the largest fraction of the physical equipment
- The actual fuel cell stack and insulation volume occupies between 24-31% of the total system volume
- For the first generation system layout, the largest single volume element was spacing between the components to account for manifolding
- Aggressive stack thermal management and internal reforming will have the greatest impact on volume reduction by impacting the size of required heat recuperators
  - Decrease cathode air requirement
  - Allow more component integration
  - Decrease manifolding and insulation requirements
- Some savings may be obtained by closer packing of rotating equipment and controls and further overall component integration and optimized layout

1. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Achieving the $400/kW system cost target appears feasible with high power density stack performance and good stack thermal management.

- System cost estimates range from $351 to $666 per kW for 5 kW SOFC APU systems
- Fuel cell stack cost and balance of plant (reformer and recuperators) are the key cost drivers for the 5kW net system
- As achievable power density increases, the cost of purchased components such as rotating equipment becomes a key cost driver
- Increasing the power density from 0.3 W/cm^2 to 0.6 W/cm^2 saves $112/kW assuming similar system efficiency
- Aggressive stack thermal management could save $64/kW while poor stack performance and thermal management can result in a penalty of $139/kW
  - Aggressive stack management reduces recuperator area and air movement requirements
- Using low/no sulfur fuel can save $35/kW from simpler system configuration (not considering alternative reformer technology)
  - A zinc sulfur removal bed is not required
  - An anode recuperator is not required

The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Performance, cost, and size of planar SOFCs offer significant opportunity in a wide range of applications.

- Estimated performance and cost appear:
  - Very competitive for APUs and distributed generation technologies
  - Very attractive for stationary markets
- Performance, size and weight may have to be further improved for key transportation markets
- The impact of lower volume production must be considered for some markets
- The impact of system capacity (modules of 5kW stacks units) should be considered for larger-scale applications
- First order risk exists in that publicly available information of a stack demonstration of a planar anode supported architecture operating at 650-800°C does not exist

In order to direct future development efforts most efficiently, SECA should consider the following issues and their implications.

- Impact of fuel choice (e.g. natural gas, propane)
- Impact of manufacture volume
- True limitations of thermal management and utilization versus attainable voltage/current
  - Modeling of stack to understand internal reforming, etc.
  - Thermal and reaction modeling of SOFC stack under different operating conditions
  - Start-up time verification (impact of thermal shock)
- Impact of internal reforming on system operation and prospects for “designer” fuels
- High performance insulation materials and systems
- Development of integrated components
- Sealing technology for the fuel cell stack
- Long term and cyclic system testing

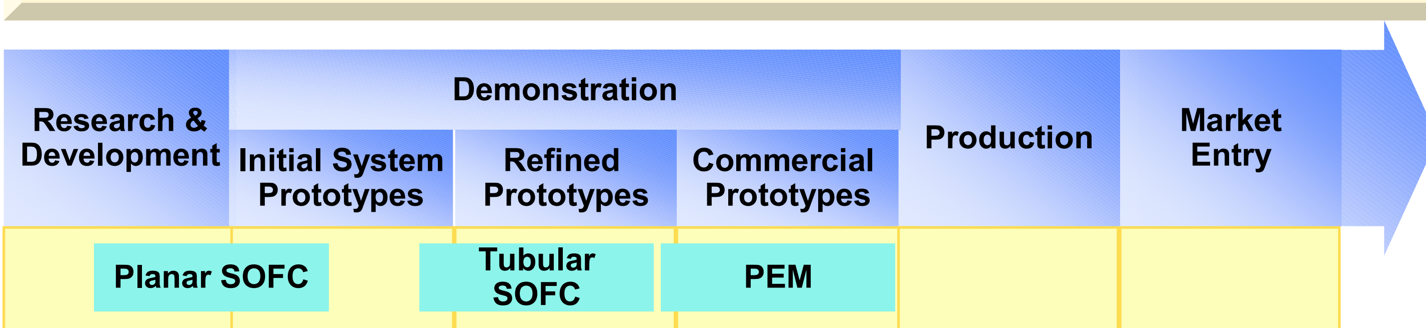
Advances in SOFC technology now appear to enable broad small-scale applications in both stationary and transportation markets.

- Planar, thin electrolyte, electrode-supported configuration improves performance significantly
  - Increases in power density (~500 mW/cm^2 or greater)
  - Lower operating temperatures (650-850°C)
  - Lower cost metallic separator plates
  - Elimination of very high temperature molten glass seals
  - Potential for higher stack efficiency
  - Reduced heat losses from lower operating temperature
- Potential for economy of scale for manufacturing
  - Geometry lends itself to high volume, low cost manufacturing techniques
  - Broad applicability is consistent with high-volume manufacturing

Effective system design and integration has not yet received sufficient attention and is critical for the development of competitive products.

Planar SOFC technology is at an earlier stage of development compared to PEM and tubular SOFC technology.

- Commercial prototype PEM systems are being demonstrated at scales ranging from about 5kW to 250 kW
- Refined tubular SOFC prototypes have been demonstrated at 100 and 250[1] kW
- Planar anode-supported SOFC is entering the initial system prototype level of development and could be applicable for small scale application



Understanding the design and cost drivers for planar SOFC technology is critical at this stage to direct further development efforts effectively.

NOTE: 1. 250KW demonstration is a combined cycle plant.

NETL would like a better understanding of planar SOFC design and cost issues related to APU[4] applications for trucks.

- PEM fuel cells have been demonstrated for automotive auxiliary power unit (APU) applications[1]
- Ballard and Daimler-Chrysler have teamed-up to develop PEM fuel cells for APUs for trucks[2]
- Planar electrode-supported SOFC technology enables small power applications such as APUs.
- BMW has recently announced a joint development program with Global Thermoelectric for APU applications for automobiles[3]

1. "Fuel Cell Auxiliary Power Unit – Innovation for the Electric Supply of Passenger Cars?", J. Tachtler et al. BMW Group, SAE 2000-01-0374, Society of Automotive Engineers, 2000.
2. "Freightliner unveils prototype fuel cell to power cab amenities", O. B. Patten, Roadstaronline.com news, July 20, 2000.
3. Company press releases, 1999.
4. APU is an auxiliary power unit

The objective of this project is to develop a conceptual design package and cost estimate for a planar SOFC system which satisfies the agreed specifications.

Deliverables

- Thermodynamic design
- System layout
- Cost estimate

Specifications

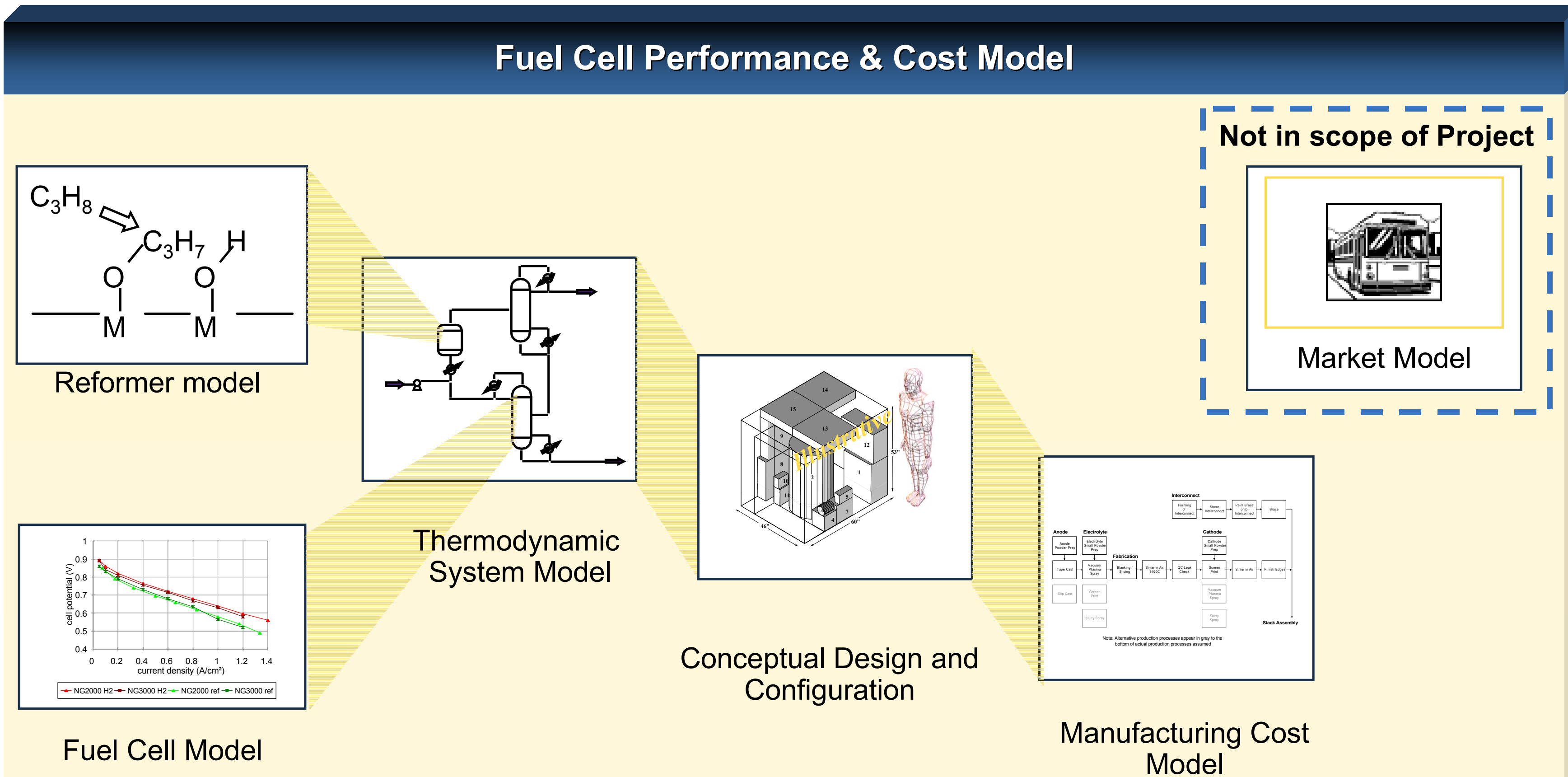
System	Stack	Balance of Plant
• Rating, 5 kW net • Mass goal < 50 kg • Volume goal < 50 liter • Operating life > 5000 h • Number of cold starts > 3000 cycles • Cold (25°C) start-up < 10 min • Time between "pit stops" ~ 1000 h (ZnO replacement) • Efficiency > 35% peak power (DC/LHV) • Surface Temp. < 45 °C	• Voltage – 42 VDC • Anode-supported technology • Operating temperature 800°C • Minimum inlet to SOFC anode 650°C	• Water use – zero • Fuel used – gasoline or Diesel • Fuel Sulfur level: sulfur free fuel (SFF) and 30 ppm sulfur containing fuel (SCF) • Oxidant – air • Cost of Balance of Plant goal < $400/kW • Ultimate goal $400/kW for system

The target application for this module is an auxiliary power unit (APU) for on-road vehicles.

The project was organized into five tasks; using two cases of fuel, sulfur-containing gasoline and sulfur-free Fischer-Tropsch Diesel.

Task 1	Task 2	Task 3	Task 4	Task 5
Kickoff	**Initial System Design**	**Cost Estimate & Sensitivity Analysis**	**System Optimization**	**Final System Design**
• Confirm design specs • Agree on stack parameters • Review initial design	• Thermodynamic system model • Size components • Layout of components	• Cost BOP components • Estimate system cost • Perform sensitivity analyses (cost, performance)	• Support CMU in Multi-Objective Optimization	• Finalize system designs
Deliverable • *Kick-off workshop held May 10, 2000 in Pittsburgh*	***Deliverable*** • *Initial system design workshop held May 30, 2000 in Baltimore* • *Refined thermodynamic model results (Section 2A)* • *Component design (Section 2B & 2C)*	***Deliverable*** • *Update on cost and design held in Pittsburgh on August 9, 2000* • *Cost and volume of components (Section 3)*	***Deliverable*** • *Scenarios are defined in Section 2* • *Cost of scenarios covering system performance (Section 3)*	***Deliverable*** • *Final system costs and volume estimates (Section 3)*

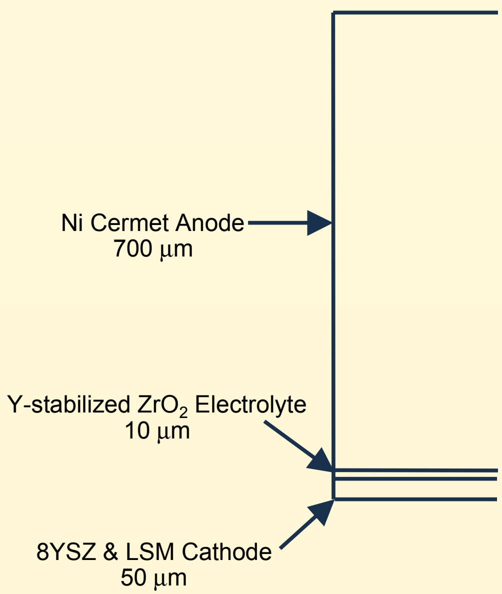
We used our multi-level RaPID™ modeling methodology to design a POX/SOFC system for APU applications.



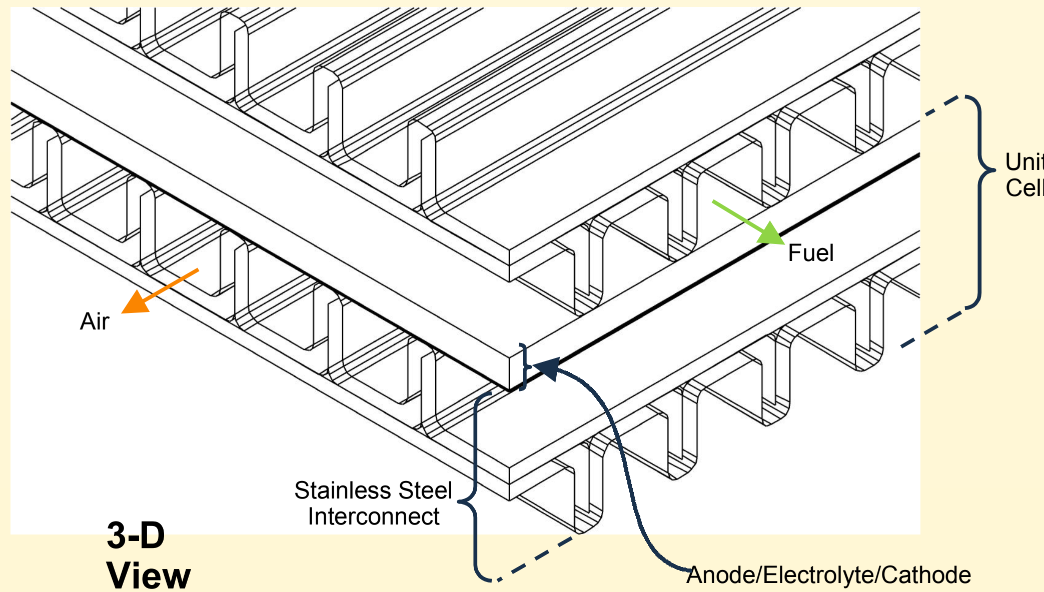
We used thermodynamic models coupled with detailed manufacturing cost models to identify the key design and cost drivers for planar technology.

For the stack cost and design assumptions, we built on previous costing work for a planar solid oxide fuel cell configuration.

Anode Supported Unit Cell



Cross-Flow Stack Configuration



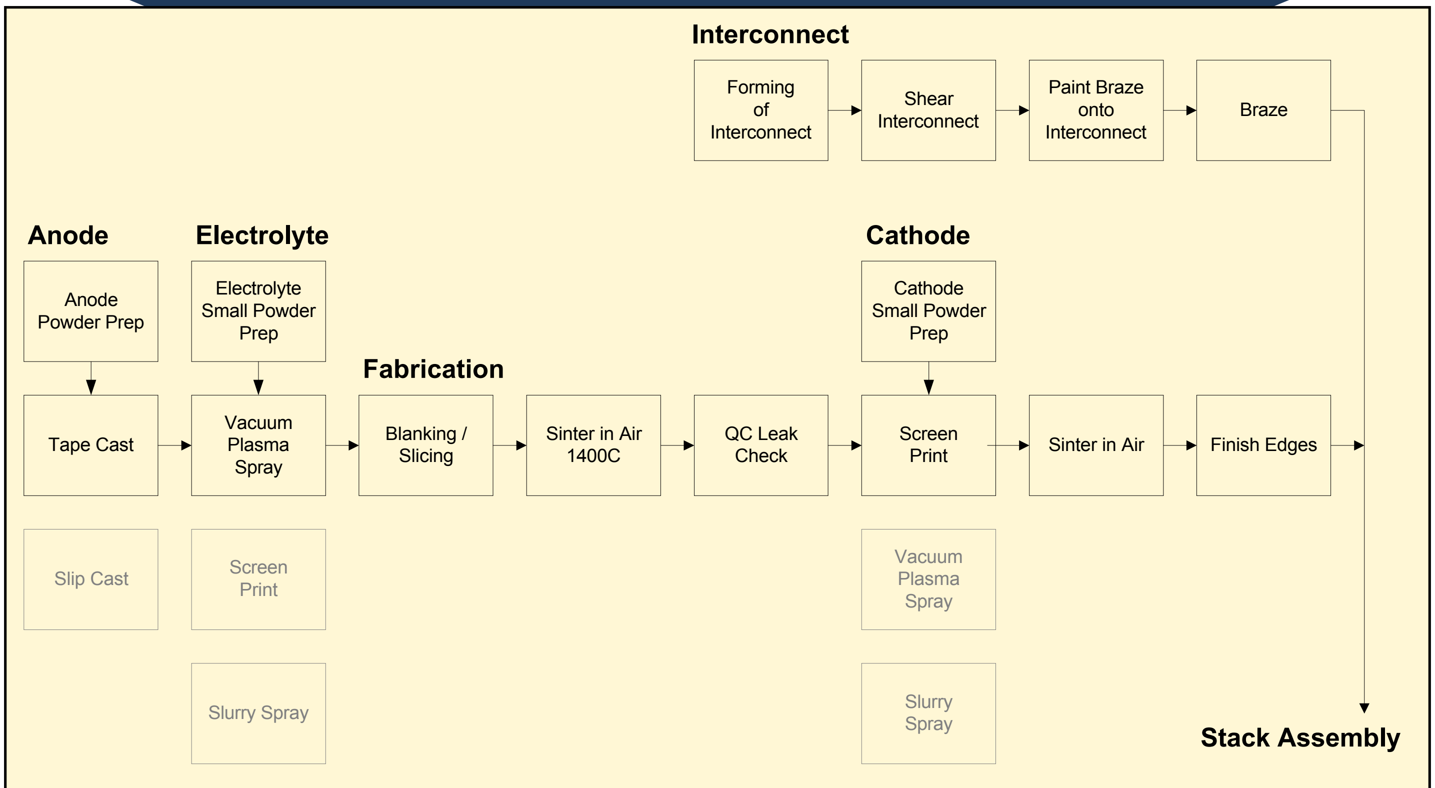
Note:

The original cost analysis was for a 25kW stack with a cell voltage of 0.7 V and power density of 500 mW/cm^2. The original cost design used an active area of 100 cm^2 and a pitch of 5 unit cells per inch.

The NETL 5kWnet design has a 300 cm^2 active area and a pitch of 5 unit cells per inch for a power density of $0.3W/cm^2$. The NETL stack operates with a single cell voltage of 0.7 V. Two cases of power density are investigated: 300 and 600 mW/cm^2.

The cost analysis of the low temperature metallic IC planar design is based on a process flow in which successive layers are individually fired.

Multi-Fired Process Flow



Note: Alternative production processes appear in gray to the bottom of actual production processes assumed

Process Flow Assumptions

- Electrical layer powders are made by ball milling and calcining.
- Interconnects are made by metal forming techniques.
- Automated inspection of the electrical layers occurs after sintering.

The cost model estimates system cost up to and including factory costs.

Excluded from Cost Model

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

Profit

Sales Expense

General Expense

Cost Model (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

Profit, sales and general expense were not included in the analysis.

The cost model contains both purchased components and manufactured components.

- We built on existing ADL cost models for SOFC stack manufacture and balance of plant
- The cost elements for the fuel cell stack contain raw material, processing, and capital recovery costs
- The cost elements for all other manufactured components include raw material and processing
- Remaining labor, indirect, and depreciation is included as a separate line item and is not distributed among the other manufactured components
- Raw material costs for system insulation and active cooling are included
  - Processing costs for system packaging are not included in analysis
  - Processing and labor for system assembly are not included

Purchased Components	Manufactured Components
• Compressor • Battery • Fuel pump • Blower (for active cooling) • Air and fuel filters • Control and solenoid valves • Controllers for compressor, pump, and blower • Control logic, processors and hardware • Piping and connectors • Fittings • Thermocouples/sensors • Wiring for sensors and valving • Insulation (high and low temperature)	• Fuel cell stack ➢ Anode ➢ Cathode ➢ Electrolyte ➢ Interconnects ➢ Stack assembly • Fuel cell stack hardware • Fuel cell packaging • Reformer • Tailgas burner • Recuperators • Zinc bed (if applicable) • Fuel Vaporizer • Recycle Eductor
Raw materials (examples) • Steel sheet • Metal foil • chemicals • Inorganic oxides • Nickel oxides	

The performance and raw material cost of anode-supported SOFC stacks make them significantly less costly than all-ceramic designs.

SOFC Technology	Comparison of Stack Structure Cost				
	g/cm^2	$\$/m^2$	Power Density		Cost (Materials and Processing) $/kW
			mW/cm2	kW/kg	
Planar Metal Interconnect (Oct 1999 Study)	1.7	$429	500	.24	$86
1997 Updated Planar All Ceramic	1.1	$753	200	.38	$377

Note:
The original cost analysis for the planar metal IC design was for a 25kW stack with a cell voltage of 0.7 V and power density of 500 mW/cm^2. The original cost design used an active area of 100 cm^2 and a pitch of 5 unit cells per inch.

The cost per kW column includes the fabrication and assembly of the fuel cell stack tiles and interconnects. The $86/kW cost does not include **sealing of stack corners, gas manifolding to feed internal manifolds, packaging of the stack chamber, current collector and stack insulation.**

We identified eight key issues concerning the design and operation of reformer/planar SOFC systems for truck APU applications.

How can reformer / planar SOFC systems be applied to truck APUs and how much will they cost?

	System Performance	Cost	Volume & Weight
Internal Stack Thermal Management			
Power density / Operating Voltage			
Stack Fuel Utilization			
Stack Thermal Mass		?	
Recuperator			
Parasitics			
Reformer efficiency			
Insulation			

● Critical ◓ Important ○ Not Leveraging

The cost and design study aimed at identifying how and to what extent these issues affect performance, cost, size, and weight.

Several key assumptions have guided this analysis including the SOFC stack operating parameters and system production volume.

- Production volume: 2.5 GW/yr (500,000 units)
- SOFC stack design parameters
  - Stack operating temperature: 800°C
  - Minimum gas stack inlet temperature 650°C*
  - Cell voltage 0.7 V
  - Power density of 0.3 W/cm^2 & 0.6 W/cm^2 (see pages 37, 38 for details)
  - Pitch of 5 cells/inch
  - Geometry: square cells
  - Total voltage 42 DC
  - Single stack
  - 90% fuel utilization at anode
- Compressor and pump efficiencies 75%
- Duty cycle, Load profile: assume constant load, on-off control
- Fuel
  - Sulfur containing fuel: Gasoline, 30 ppm sulfur (using representative model mixture)
  - Sulfur-free fuel: Fischer-Tropsch Diesel (modeled as n-hexadecane)

Note: *Literature reports have shown operation with a greater approach temperature than 150°C. "System Demonstration Program at Ceramic Fuel Cells Ltd. In Australia", K. Foger and B. Godfrey, in Fuel Cell 2000 Proceedings, July 10-14, 2000, Lucerne, Switzerland.

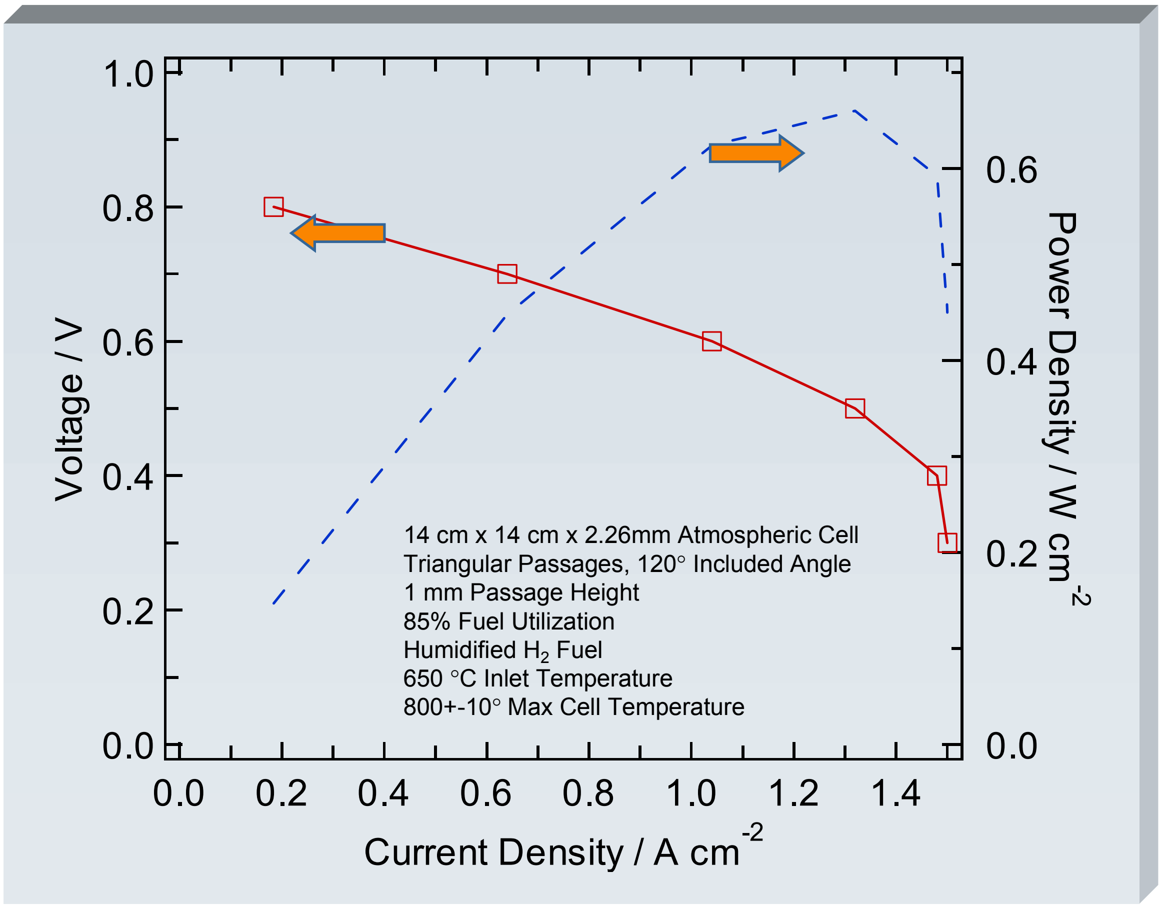
The base case takes a cell voltage of 0.7 V and a power density of 0.3 W/cm² with 90% fuel utilization in an anode supported solid oxide fuel cell.

- The design value of cell voltage reflects a compromise between electrical efficiency and power density (or stack size):
  - At low fuel utilization (<5% conversion), researchers have demonstrated a single cell performance of 1.4 W /cm^2 at 0.7 V and 1.75 W/cm^2 at 0.5 V[(1)]
  - With increasing fuel utilization, the voltage corresponding to maximum power density shifts to higher voltages. This imposes a lower limit on the cell voltage
  - With increasing fuel utilization the Nernst potential (or the chemical driving force) decreases. This imposes an upper limit on the cell voltage
- To our knowledge there is no public literature data for high utilization of either pure hydrogen or reformed fuel in an anode supported SOFC stack:
  - A single anode supported SOFC cell gave 0.36 W/cm^2 with ~85% utilization of *synthetic reformate* at 800°C and 0.7 V[(2)]
  - Typically, the average power density per cell in a stack is lower than that measured in a single cell
- Given these uncertainties, we feel that our assumption of 0.3 W/cm^2 at 90% utilization in a stack appears reasonable

Experimental verification of power density (0.3 - 0.6 W/cm²) at high fuel utilization is critically important.

NOTES:
1, J-W Kim, A. V. Virkar, K-Z Fung, K. Mehta, S. C. Singhal, *J. Electrochem. Soc.*, 146 (1999) 69.
2. R. K. Ahluwalia, H. K. Geyer, E. D. Doss, R. Kumar, and M. Krumplet, Presentation at the NETL workshop on fuel cell modeling, Morgantown, WV (2000).

At 85 % hydrogen utilization, the cell performs poorly above 0.8 V and below 0.3 V. At 0.7 V, a power density of 0.45 W cm^{-2} has been shown[1].



1. R. K. Ahluwalia, H. K. Geyer, E. D. Doss, R. Kumar, and M. Krumplet, Presentation at the NETL workshop on fuel cell modeling, Morgantown, WV (2000). Data is on a single cell, pure hydrogen feed.

Stable operation of the stack requires balancing of heat generation from electrochemical reactions with heat removal through three mechanisms.

- Conductive losses to the environment
  - Heat losses help cool the stack
  - Excessive heat losses can lead to local stack cooling below active temperature resulting in loss of self thermal stabilization
  - Structural integrity might be compromised by excessive temperature gradients inside stack
  - Excessive heat losses make maintaining acceptable skin temperature challenging
- Convective losses to fuel gas and air
  - Main mechanism for heat removal
  - Temperature rise in anode and cathode limited by activity and structural concerns (for this study, assumed to be 150°C)
  - Limit in approach temperature requires high excess air (about 7 times)
  - Small approach temperature requires efficient high-temperature recuperators with associated cost, volume, and weight impacts
- Chemical cooling with internal endothermic reforming
  - Could remove substantial portion of heat
  - Increases system efficiency
  - Carbon formation and thermal temperature management are unresolved issues
  - Supplying sufficient steam is a challenge without significant system impacts

The mechanisms employed for stack thermal management directly impact the specification of the recuperators, parasitics, and insulation volume.

- The assumed allowable approach temperatures (~150°C) for the cathode and anode have several system implications
  - Use of high temperature exotic materials for the recuperators
  - Higher levels of excess air for cathode cooling
  - Larger heat exchange area for heat recuperation
  - Larger POX and Tailgas burner volume to encompass surface area
- Parasitic duty increases with increase in excess air requirement
  - The increase in cathode air requirement impacts the specification of low cost blowers versus more expensive compressors from system pressure drop
  - Parasitic duty impacts required size of fuel cell (more stack area and lower efficiency)
- The ability to internally reform fuel at the anode makes reformer efficiency a somewhat less critical issue
- All component specifications directly impact the required volume (and associated cost) for insulation
  - A high temperature and low temperature insulation will be required
  - Mechanism for active or forced cooling will be needed in order to reduce insulation volume

The system design section is organized into three parts.

- An overview of the system modeling will be presented for the base case
  - Detailed results for the base case and other cases are presented in Appendix A
- The design of the key components for the base case is presented at a high level with details found in Appendix C
- The component volume and system configuration completes the section
- Cost analysis and sensitivity is presented in Section three

Five separate cases were modeled to investigate the effects of different operating conditions and fuel type.

- Base Case
  - Realistic stack thermal management
  - Realistic power density
- Case 1 - Best Case Scenario
  - More aggressive stack thermal management assumptions
  - Assumes higher achievable power density
- Case 2 - Conservative Scenario
  - Conservative stack thermal management
  - Conservative fuel utilization of 70%
  - Assumes realistic power density
- Case 3 - Base case with higher achievable power density
- Case 4 - Sulfur free fuel
  - Similar assumptions as base case
  - Hexadecane as model Fischer-Tropsch Diesel fuel

Five separate cases were modeled to investigate the effects of different operating conditions and fuel type.

	Base Case	Case 1 Improved Stack Design	Case 2 Poorer Stack Operation	Case 3 Higher Power Density	Case 4 Sulfur-free Fuel
Cathode Air Inlet Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Anode fuel Utilization	90%	90%	70%	90%	90%
Fuel	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	0 ppm S Diesel
Power density, W/cm^2	0.3	0.6	0.3	0.6	0.3

NOTES.
1. Case 3 has the same performance (efficiency) as the base case except that the fuel cell stack operates with a higher power density (0.6 W/cm^2 compared with 0.3 W/cm^2).
2. Case 4 has the same power density as the base case except that the fuel is sulfur-free Fischer-Tropsch Diesel.

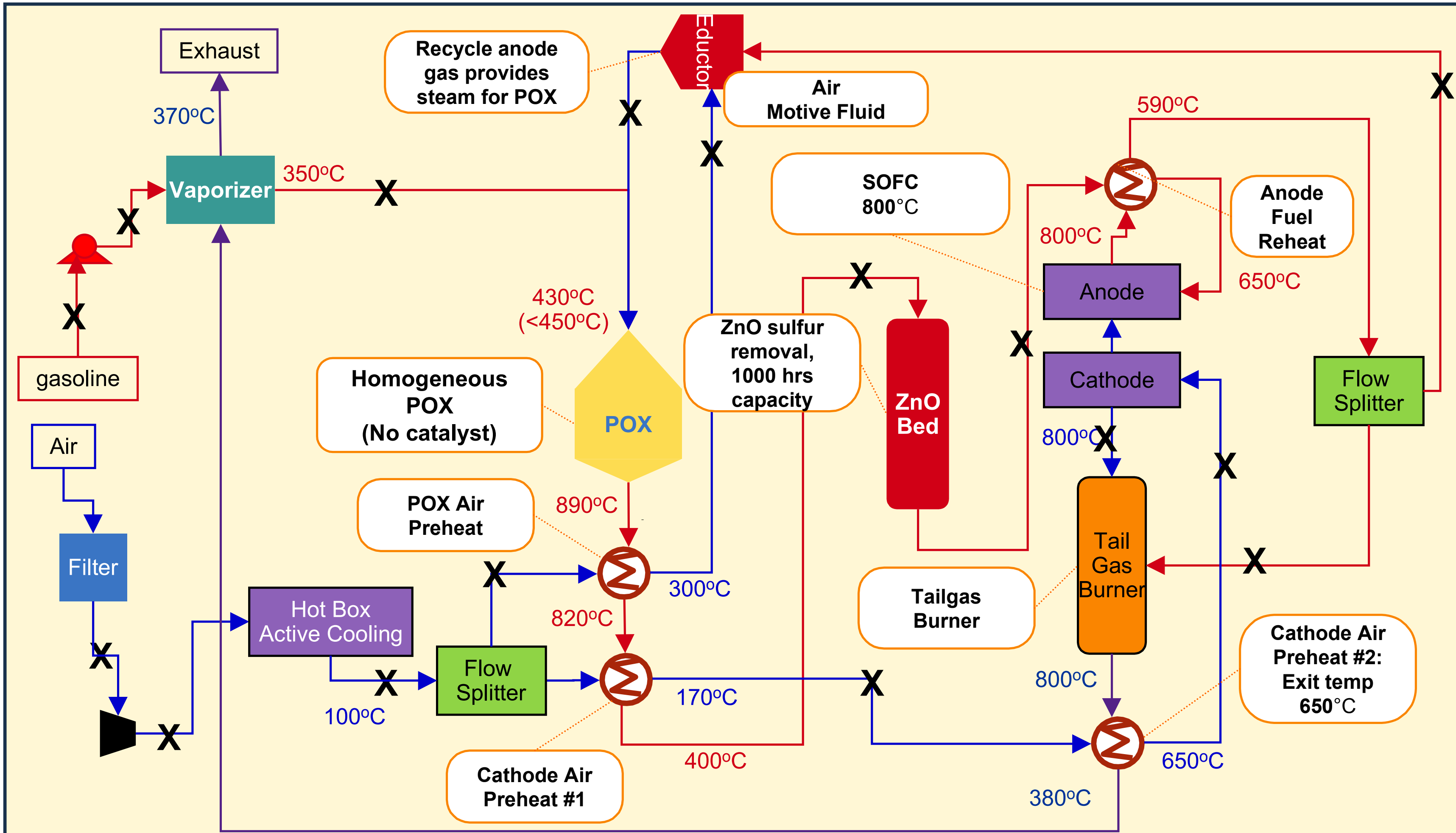
The following assumptions were used in all four sulfur fuel design cases (base case, #1, #2 and #3).

Sulfur Fuel Case Assumptions

- POX reformer equivalence ratio 3.0[1]
- ZnO sulfur removal bed:
  - Operating temperature 400ºC
  - Pressure drop 0.01 atm
- Fuel cell:
  - Operating temperature = 800ºC
  - Anode inlet temperature = 650ºC (in all cases)
  - Single cell voltage 0.7 V
- Anode effluent:
  - One third recycled to POX reformer
  - Two thirds burned in Tailgas burner
- Pump and compressor efficiency 75%[2]
- Gasoline modeled as seven hydrocarbon mixture and sulfur modeled as hydrogen sulfide
- Exhaust stream enthalpy used for fuel vaporizer duty

NOTES.
1. Phi or fuel equivalence ratio is defined as $(fuel/air)_{actual}/(fuel/air)_{stoichiometric}$; a phi of 3 is 1/3 of stoichiometric air.
2. Pump and compressor efficiency for equipment in the size range for this application may not be attainable.

Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power.



X Piping or manifold needed, others are integrated into various process units.

System efficiency targets of 35 percent can be met with sufficient stack thermal management[5].

	Base Case	Case 1	Case 2	Case 3	Case 4
Anode Fuel Utilization	90%	90%	70%	90%	90%
Fuel Cell Efficiency[3]	49%	49%	38%	49%	49%
POX Effluent Temperature	890ºC	890ºC	940ºC	890ºC	910ºC
Estimated POX (with recycle) Efficiency[1]	87%	87%	91%	87%	87%
Cathode Inlet Air Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
Required Cathode Excess Air	760%	330%	1,100%	760%	750%
Required Compressor Pressure[2]	1.28 atm	1.19 atm	1.39 atm	1.28 atm	1.29 atm
Parasitic Loads	**750 W**	**260 W**	**1,700 W**	**750 W**	**770 W**
Exhaust Temperature	370ºC	590ºC	370ºC	370ºC	380ºC
Resultant Overall Efficiency[4]	**37%**	**40%**	**26%**	**37%**	**37%**
Required Fuel Cell gross power rating, kW	**5.75**	**5.26**	**6.70**	**5.75**	**5.77**

1. LHV of the POX outlet stream divided by the LHV of the fuel inlet stream not including the anode recycle inlet. Does not include internal fuel cell reforming.
2. Required pressure to overcome air side pressure drops. Slightly different tube diameters and geometries were used in each case to keep the pressure requirement as low as possible without incurring large volume increases.
3. Fuel cell efficiency is defined as the product of the fuel utilization, voltage (electrical) efficiency and thermodynamic efficiency. Fuel cell efficiency is equal to (Fuel utilization) * (operational voltage/open cell voltage) * (ΔG_{rxn}/LHV fuel). Assume an open cell voltage of 1.2 volts for all anode reactions.
4. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)
5. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power. Thermal management of the stack refers to the maximum allowable temperature gradients allowable in the stack due to thermal stress. Thermal management also encompasses the amount of fuel that can be internally reformed at the anode which can serve to regulate the temperature in the stack.

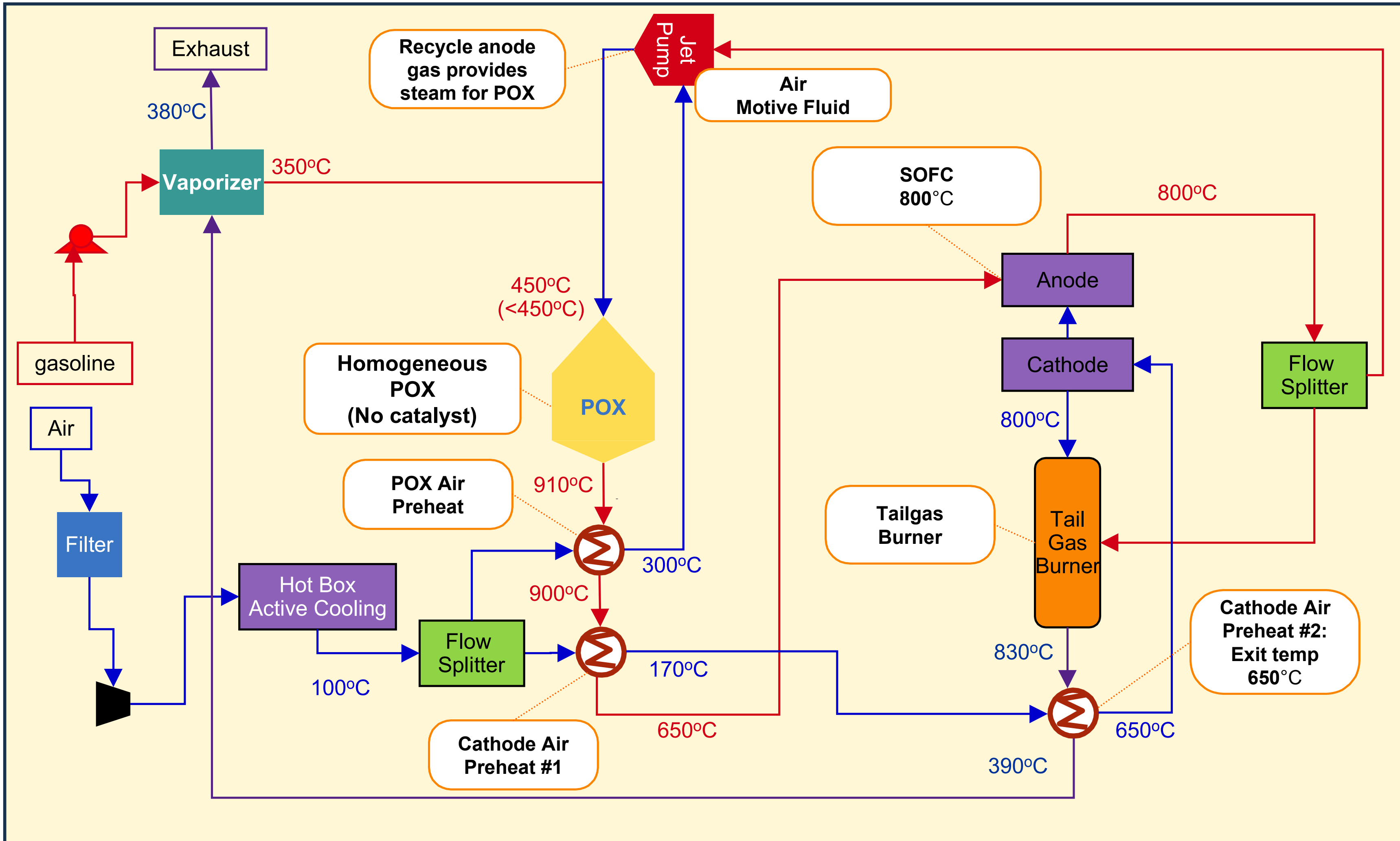
We made two changes to the sulfur free fuel case (case 4) from the initial NETL design.

- We used pure air instead of cathode air exhaust for the POX oxygen feed
  - Eliminates cathode exhaust flow splitter
    - Control valves are not available at these high temperatures (~700-800°C)
    - Cathode splitter would be difficult at start-up (equivalence ratio control)
  - Pressure requirement on compressor decreased
    - Air-side pressure drops are in parallel instead of series
  - Flow requirement on compressor increased slightly
    - POX air requirement is small compared to cathode air requirement
    - Decreased pressure requirement offsets this increase
  - Anode fuel partial pressure increased (reduced nitrogen dilution)
- We used two integrated POX heat exchangers, one for POX air preheat and one for primary cathode air preheat
  - Overall POX reactant preheat to 450°C benefits POX operation
  - Decreased the required size of secondary cathode preheater
  - Cooling the POX effluent decreased the compressor load
    - Lower anode inlet temperature (used 650°C in all cases)
    - Decreased cathode excess air requirement

The system integration of the sulfur-free case is simplified with the removal of the zinc oxide sorbent bed.

- POX effluent can conceivably enter the SOFC anode without conditioning
  - However, it is practical to use POX syngas enthalpy to heat feed gases for a lower anode inlet temperature (650°C)
  - Cooler anode inlet temperature reduces the cathode excess air requirement
- Small, but potentially costly, Anode Recuperator heat exchanger can be eliminated
  - POX syngas does not need to be cooled to 400°C (for sulfur removal in sorbent bed) and then reheated
  - An “off-the-shelf” compact heat exchanger does not exist for the anode stream conditions (high temperature, reducing conditions)
- Maintenance cost and effort is reduced since ZnO sorbent bed is not required

System integration for the sulfur-free case is conceivably simpler without the zinc sorbent bed.



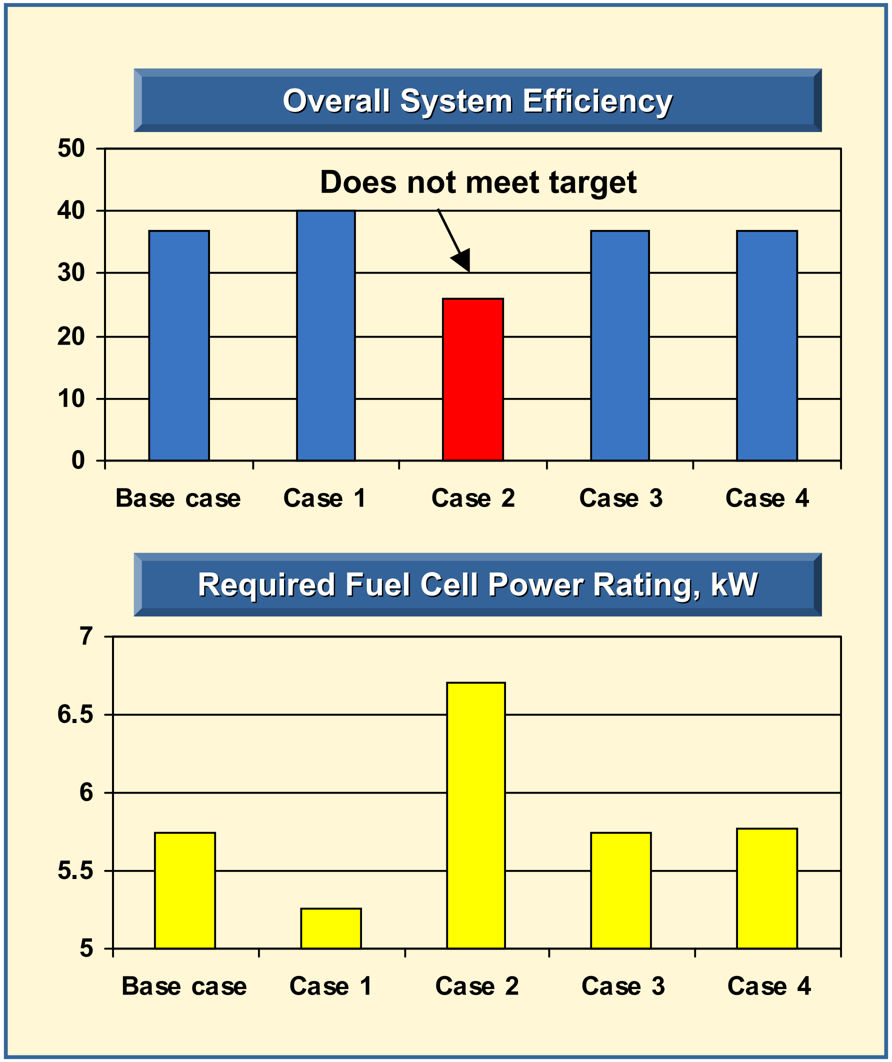
The sulfur free fuel case is very similar to the base case in performance. Savings in excess air are balanced by a slightly higher pressure drop[3].

	Base Case	Case 4 Sulfur Free
Anode fuel Utilization	90%	90%
Fuel Cell Efficiency[4]	49%	49%
POX Effluent Temperature	890ºC	910ºC
Estimated POX (with recycle) Efficiency[1]	87%	87%
Cathode Inlet Air Temperature	650ºC	650ºC
Required Cathode Excess Air	760%	750%
Required Compressor Pressure[2]	1.28 atm	1.29 atm
Parasitic Loads	750 W	770 W
Exhaust Temperature	370ºC	380ºC
Resultant Overall Efficiency[5]	**37%**	**37%**
Required Fuel Cell gross power rating, kW	**5.75**	**5.77**

1. LHV of the POX outlet stream divided by the LHV of the fuel inlet stream not including the anode recycle inlet. Does not include internal fuel cell reforming.
2. Required pressure to overcome air side pressure drops.
3. Pressure drop could be reduced by redesign of cathode at expense of fuel cell stack size and weight.
4. Fuel cell efficiency is defined as the product of the fuel utilization, voltage (electrical) efficiency and thermodynamic efficiency. Fuel cell efficiency is equal to (Fuel utilization) * (operational voltage/open cell voltage) * (ΔG_{rxn}/LHV fuel). Assume an open cell voltage of 1.2 volts for all anode reactions.
5. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)

System efficiency targets can be met under most circumstances.

- System efficiency of greater than 35% is easily achievable:
  - Typical efficiency 37%
  - 40% efficiency appears achievable
  - Poor stack thermal management can significantly impact efficiency
- Poor stack management will make attaining system efficiency goals difficult
- Use of sulfur free fuel does not dramatically change system performance from base case sulfur containing fuel operation



Individual components have been distributed among the major sub-systems.

Reformer	Fuel Cell	Recuperators	Balance-of-Plant
◆ Homogeneous gas phase POX reformer[1] ➢ POX air preheater ➢ Air, fuel, recycle mixer ➢ Eductor ➢ Primary cathode air preheater ◆ ZnO sorbent bed	◆ Fuel Cell Stack (Unit Cells) [3] ◆ Balance of Stack[4]	◆ Anode recuperator ◆ Tailgas burner[2] ➢ Fuel vaporizer ◆ Secondary cathode air preheater	◆ Startup power ➢ Start-up battery ➢ Blower for active cooling ➢ Switching regulator for recharging ◆ Control & electrical system ➢ System sensors ➢ Controls ➢ System logic ➢ Safety contactor ◆ Rotating equipment ➢ Air Compressor ➢ Fuel Pump ◆ System insulation ◆ System piping

1. The reformer also incorporates the POX air preheater, primary cathode air preheater, air/fuel/recycle mixer, and eductor integrated inside.
2. The Tailgas burner incorporates the fuel vaporizer, and in case 2 the secondary cathode air preheater integrated inside.
3. The fuel cell stack includes cathode, anode, electrolyte, interconnects, and layer assembly, and stack assembly
4. The balance of stack includes endplates, current collector, electrical insulator, outer wrap, and tie bolts. It is assumed that the stack is internally manifolded.

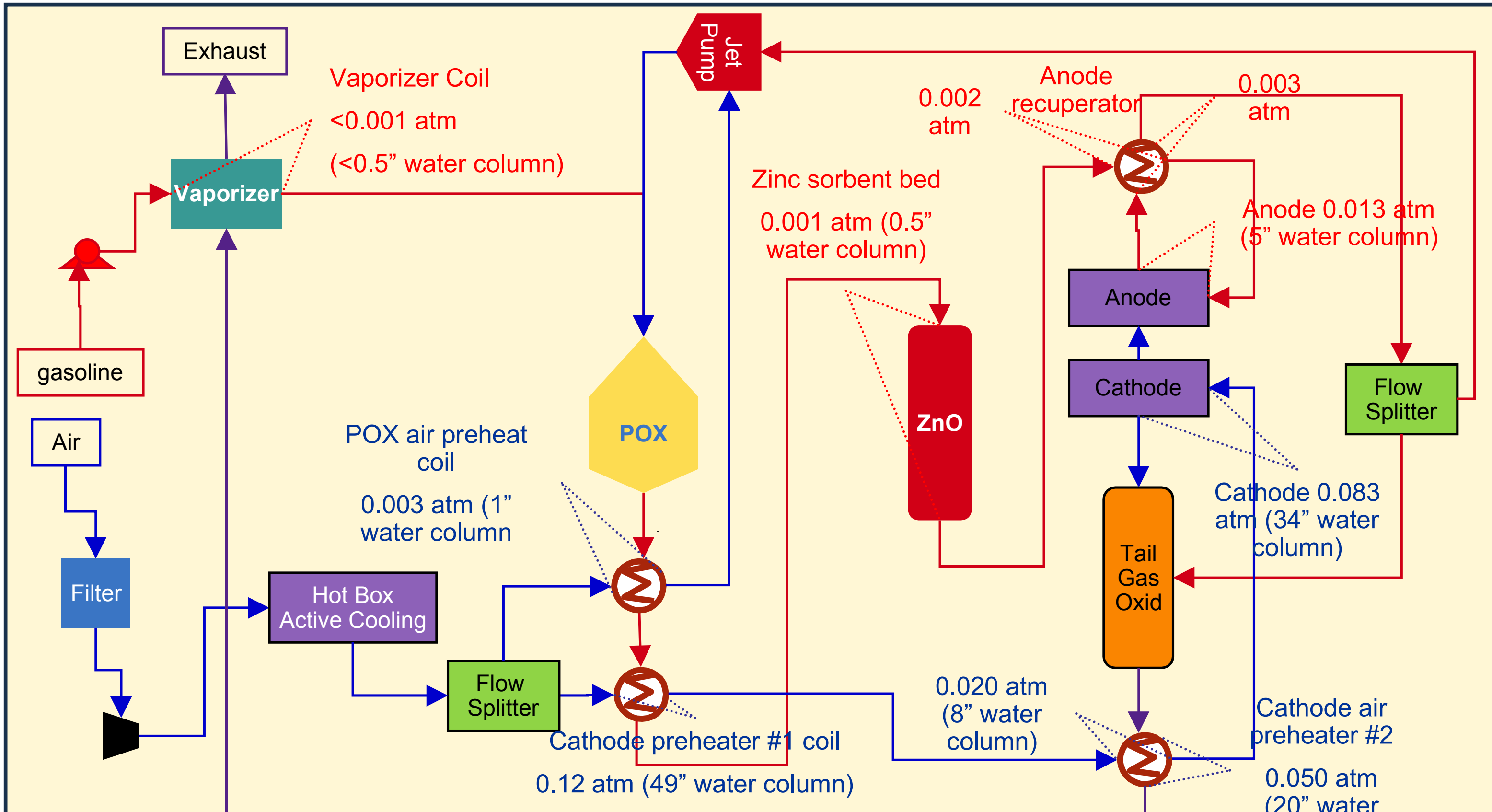
We will highlight the design approach used for the major components in the following pages.

By using anode exhaust recycle, the POX operation is limited in equivalence ratio and steam to carbon ratio before it extinguishes itself.

- The equivalence ratio upper operating point is 3.0 in the system with an anode exhaust recycle of 37% (S/C ratio = 0.5)
  - As the recycle amount increases the inlet temperature increases and amount of nitrogen (dilution) increases
  - Above an equivalence ratio (Φ) of 3.0, there is not enough oxygen present to start the reaction
- The maximum amount of anode exhaust recycle is 42% (S/C = 0.6, $\Phi = 3.0$)
  - Dilution effects limit conversion in this case
- A total POX residence time of 0.3 seconds was taken for all cases
- A total cathode residence time of 0.05 seconds was taken for all cases
  - The Tailgas burner operates with a equivalence ratio of 0.3
- The design operating point is within an acceptable window with respect to soot formation, methane/unconverted carbon, and outlet temperature

NOTES.
1. Fuel equivalence ratio (Φ) is defined as $(\text{fuel/air})_{\text{actual}}/(\text{fuel/air})_{\text{stoichiometric}}$; a Φ of 3 is 1/3 of stoichiometric air.
2. Steam to carbon (S/C) is defined as the ratio between the moles of water in the inlet stream to the moles of combustible carbon.

The air compressor outlet pressure depends on the pressure drop requirements in the cathode air stream.



Notes: Air filter, active cooling, and flow splitter pressure drops were not analyzed but estimated at 0.01 atm (5" H_2O). Both air side and reformate side pressure drop totals include the 0.04 atm drop in Cathode air preheater #2.

Total reformate side pressure drop is approximately 0.07 atm, while the total air side pressure drop is approximately 0.28 atm (excess air 760%).

We integrated heat exchangers to take advantage of recuperation of enthalpy from the POX and Tailgas burner effluent streams.

- Integrated POX also containing:
  - POX Air Preheater
  - Primary Cathode Air Preheater
- Integrated Tailgas burner also containing:
  - Secondary Cathode Air Preheater (for Case 1)
  - Fuel Vaporizer
  - Pressure drops were prohibitive in base case, Case 2, 3, and 4 to integrate secondary cathode air preheater
- For high excess air requirements, compact, finned heat exchangers will significantly decrease exchanger volume and pressure drop
  - Flow can be split into as many passages as necessary
  - Fins increase effective heat exchange area
- A compact heat exchanger for the Anode Recuperator heat exchanger was used for all cases
- A compact heat exchanger for the secondary cathode air preheater was used for the high excess air cases (Base case, Case 2, 3 and 4)

For the cost analysis, all heat exchange area (integrated and stand-alone) was treated as a coil encased in a shell.

System integration directly impacts system performance and configuration in the areas of start-up time and system volume.

- System integration reduces insulation requirements (and resultant system volume)
- In order to maximize system performance, key recuperators were integrated wherever possible
  - System integration is restricted by tolerable pressure drops (and resultant compressor duty)
- The degree of integration placed restrictions for operation under start-up conditions
- The integration used placed restrictions on the system cold-start heat-up time
- An optimum system design may require the use of dedicated blowers and burner to aid in stack heat-up under cold start-up conditions

We used the enthalpy of the tailgas burner exhaust to indirectly heat the stack up to its initial operating temperature.

- The tailgas burner is fed liquid fuel during cold start-up
  - Vaporizer integrated in the tailgas burner is not yet functional
- Steady-state mass flow of cathode air is used (i.e. compressor is not oversized for cold start-up)
  - Equivalence ratio of 0.3
  - Outlet temperature of <850°C
- The battery will drive the compressor and fuel pump during heat-up period
- Stack thermal properties determine the heat-up time
  - To avoid thermal stresses in the stack, we were limited by a maximum approach temperature (cathode air temperature vs. stack temperature)

We assumed that the stack remains in its reduced state during shutdown.

With existing compressor capacity, the minimum time required for cold stack heat-up is 14 minutes, neglecting limits of approach temperature.

- However, there is a limit on the approach temperature the stack materials can withstand
  - We assumed a constant temperature gradient between the inlet cathode air and the stack to estimate the required cold start-up time
- With a 150°C approach temperature, stack heat-up time range from 35-70 minutes depending on stack power density
- If a 300°C approach temperature were tolerable, the heat-up time is reduced to 13-27 minutes

Notes:
1. Approach temperature is defined as difference of stack operating temperature and cathode air entrance temperature

To achieve a 10 minute cold-start, a 3 times larger compressor is necessary to accommodate higher air flow rates.

- The base case compressor cannot achieve a 10 minute cold start, even when operating at full capacity
- In the base case, with an approach temperature of 150°C, the following are needed to heat the stack up to a 650°C operating temperature
  - Triples compressor capacity (from 41 SCFM to 134 SCFM)
  - Doubles Tailgas burner volume from 6.7 to ~15 L
  - Triples the pressure drop through the cathode from 0.08 to ~0.3 atm
  - Increases the size and pressure drop of secondary cathode preheater

Impacts	
Cost	**Volume**
Approximately + 15%	Approximately + 33%

These provisions were *not* included in the base case calculations.

1. Standard conditions of 60°F, 1 atm
2. Approach temperature is defined as difference of stack operating temperature and cathode air entrance temperature

During start up, the pump and compressor could run off of the existing truck batteries.

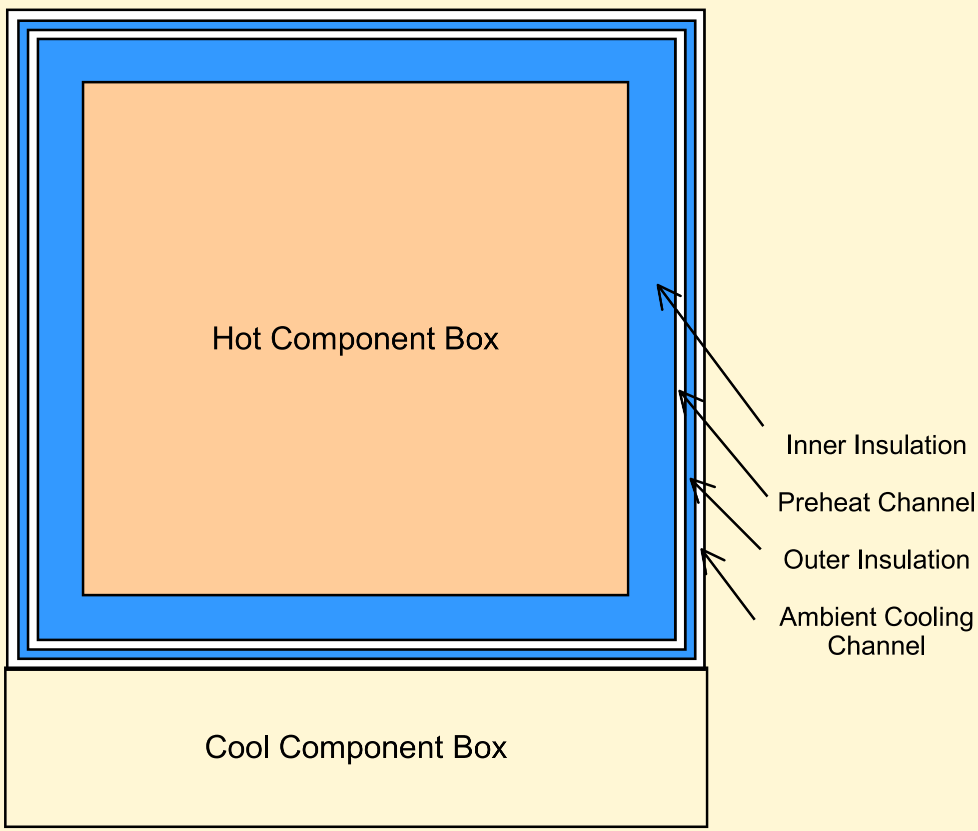
Start up Energy Requirements	
Power Requirement	340 W
Duration	20 minutes
Energy Requirement	113 Wh
Energy of Batteries	24V * 150Ah = 3600 Wh
Percent discharge	**3.1%**

Such a small discharge should pose no problem for the truck batteries.

The system is divided into a hot component box with active air cooling to decrease insulation requirements, and a cold components box.

NETL SOFC System Layout

Note: NOT TO SCALE.



Hot Component Box:

- Fuel cell stack
- POX reformer
- Anode fuel heat exchanger
- Tailgas burner
- ZnO bed (sulfur removal)
- Recuperator Heat exchangers
- Eductor

Cool Component Box

- Control System
- Air compressor and filter
- Fuel pump and filter
- Air blower for active cooling
- System battery

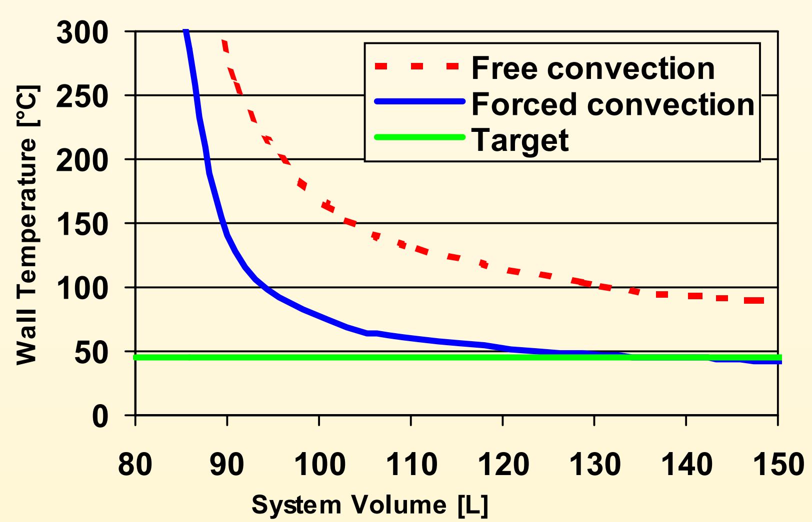
The volume of insulation required for a 45°C skin temperature of the hot box is prohibitive, if free convection is the only mode of heat removal.

Overview

Volume Calculation Premise:

- The skin temperature can be calculated for any volume by setting the heat being removed by free convection equal to the heat being conducted through insulation.
- The temperature of the hot component box is a constant 650°C. The high temperature zones are contained inside the hot components.
- With a skin temperature of 100°C, the volume of insulation is 43 L and the total volume is 127 L. with only free convection.
- For a skin temperature of 45°C, the total volume is 133L with forced convection.

Modeling Results



Other modes of heat removal, in addition to natural convection and conduction, are needed to reduce insulation volume.

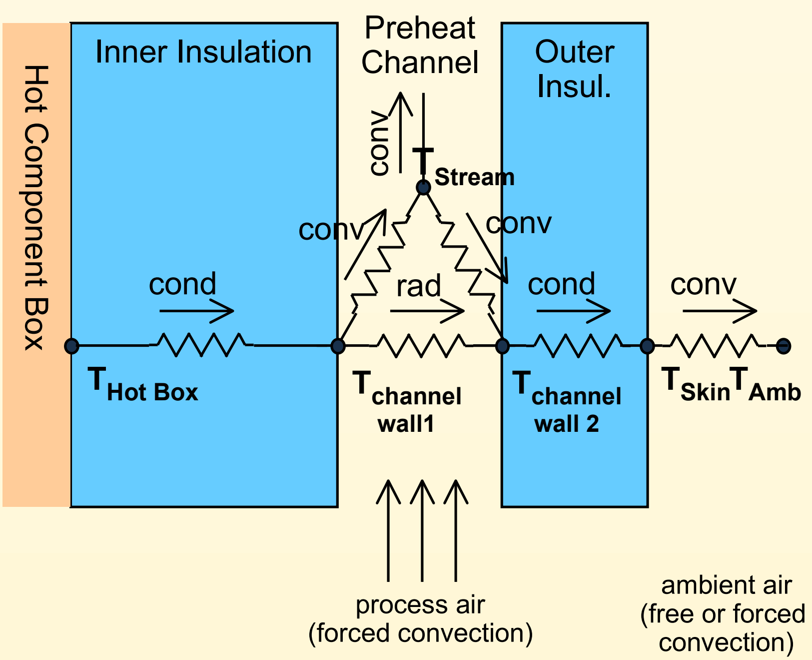
We modified our heat transfer model to include active cooling to reduce insulation volume.

Overview

Active Cooling Premise:

- Process air can be used to remove a portion of the heat loss requirement in a more efficient way.
- Additional volume reduction could be achieved with a dedicated blower/compressor.
- The heat from the hot component box is taken away by both the process air and the external ambient air. Heat is transferred through the channel by convection with the process air and by radiation.
- Inputs for the model include:
  - Volume of hot component box
  - Temperature of hot component box
  - Skin temperature of insulated box
  - Ambient air temperature
  - Insulation properties
  - Flow rate of process air

Diagram of Equivalent Circuit

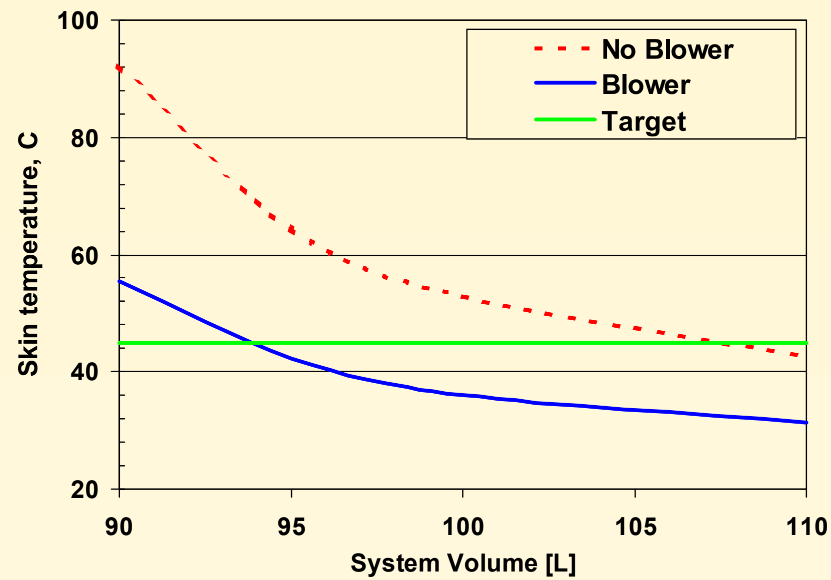


The system volume is reduced by using process air for active cooling. Further reductions can be obtained by using a blower on the outside wall.

Overview

- Using only the process air for active cooling the skin temperature is 45.0 °C with a total system volume of 108 L.
- If an extra cooling channel and blower are used, system volume is reduced to 94 L at 45°C.
- With a skin temperature of 60°C, the total system volume is reduced to 96 L.
- The model could be refined to take into account heat transfer from individual components inside the hot component box.

Modeling Results



0.3 W/cm² fuel cell (14.8 L)
Hot component box temperature is 650°C
Air exit temperature is 100°C*

*at very low volumes, exit temperature is greater than 100°C

For all cases, a cube was used as the target shape for the hot box.

- We packed all the hot components in a box:
  - Resembling a cube as much was feasible to minimize heat loss
  - Considering manifolding and interrelationships between components
- The hot box "cube" was then insulated and equipped with active cooling
- The cold box was set to have the same footprint area as the insulated hot box
- The height of the cold box is set by the compressor dimensions
- Further system volume reduction is possible by a optimal arrangement of the components in the hot and cold boxes and the use complex shapes

Notes:
1. The hot box contains the fuel cell stack, reformer, Tailgas burner, zinc sorbent bed, and anode recuperator, and secondary cathode air preheater.
2. The cold box contains controls, compressor, blower, and fuel pump.

For all cases, a cube was used as the system configuration for packaging of the hot box component.

	Base Case	Case 1	Case 2	Case 3	Case 4
Hot Component Box Total	**33.1**	**19.6**	**47.9**	**25.7**	**30.4**
◆ Fuel cell stack	14.8 L	6.8 L	17.1 L	7.4 L	14.8 L
◆ POX reformer[1]	6.8	6.7	9.6	6.8	7.0
◆ ZnO bed	1.7	1.7	1.7	1.7	n/a
◆ Tailgas burner[2]	6.7	4.0	10.2	6.7	6.7
◆ Anode preheat exchanger[3]	0.3	0.3	0.6	0.3	n/a
◆ Secondary cathode air HEX[3]	2.7	n/a	8.7	2.7	1.9
Cold Component Box Total	**10.9**	**6.7**	**16.8**	**10.9**	**10.9**
◆ Air compressor/filter	7.0 L	2.9 L	12.9 L	7.0 L	7.0 L
◆ Control system	0.5	0.5	0.5	0.5	0.5
◆ Fuel pump	0.7	0.7	0.7	0.7	0.7
◆ Active cooling blower	2.7	2.7	2.7	2.7	2.7

1. The POX reformer includes volume for the POX air preheater and the primary cathode air preheater
2. The Tailgas burner includes volume for the vaporizer. In case 1, the secondary cathode air preheater is integrated into the Tailgas burner.
3. The anode preheater and the secondary cathode air exchanger are configured as compact finned cross flow cube heat exchangers
4. The volume of the eductor is negligible and will be integrated with the POX reformer
5. A deep cycle battery would occupy an additional 8.7L (52 amp-hour capacity, 12V) and is not included in volume totals shown.
6. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

The packaged system volume ranges from 60 to 145 liters.

	Base Case	Case 1	Case 2	Case 3	Case 4
Hot component Box					
◆ Component Volume	33.1 L	19.6 L	47.9 L	25.7 L	30.4 L
◆ Packaged volume	53.2	34.6	71.9	40.7	51.3
◆ Insulation volume	8.0	6.5	9.2	5.1	8.8
◆ Volume for active cooling	4.6	3.2	5.6	3.4	4.6
◆ Piping volume	14.6				
◆ Empty space volume[4]	5.6	15.0	24.0	15	20.9
Cold component Box					
◆ Component Volume	10.9 L	6.7 L	16.8 L	10.9 L	10.9 L
◆ Packaged volume	35.1	15.8	57.0	26.9	34.3
◆ Empty space volume	24.2	9.1	40.2	16.0	23.4
◆ **System Volume, L**	101	60	145	76	99

Notes:
1. A "hot box" contains the fuel cell stack, POX reformer, Tailgas burner, recuperators, eductor, and zinc bed
2. A "cold box" contains the compressor, fuel pump, active cooling blower, and controls
3. Piping manifolding was estimated to be 284 inches of 1 inch tubing in the base case for a volume of 14.6L of piping in the base case. Piping estimates for the other cases were not estimated.
4. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Empty volume constitutes from 34 - 43% of the total volume.

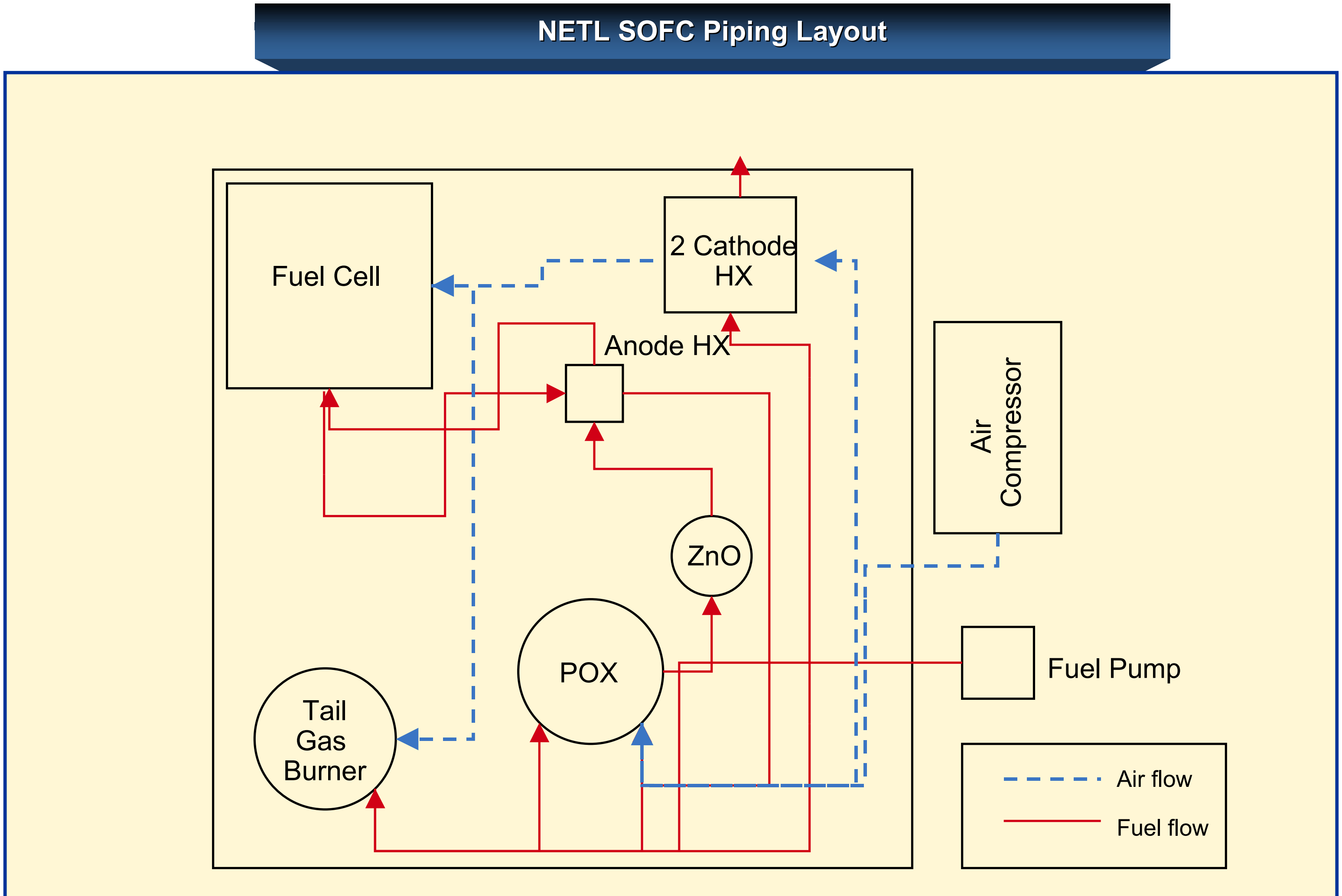
24 feet of 1" tubing[1] will be required to connect all the components together in the base case configuration.

	Piping Estimates		
	Total Length Inches	**Number of Sections**	**Process Fluid**
Compressor to POX	16	3	Cathode air to 1° cathode recuperator (in POX)
Tee to POX	11	1	POX air to POX reformer
POX to 2° Cathode recuperator	13	1	Cathode air from 1° recuperator to 2° recup.
2° Cathode recuperator to FC stack cathode	15	2	Feed cathode air
FC stack cathode to Tailgas burner	5	1	Cathode exhaust air
Fuel pump to Tailgas burner (for startup)	47	2	Liquid fuel for start-up
Tailgas burner to POX (vaporized fuel)	17	2	Vaporized fuel (vaporizer in Tailgas burner)
POX to ZnO sorbent bed	29	2	Reformate
ZnO sorbent bed to Anode recuperator	7	2	Reformate
Anode recuperator to FC anode	30	2	Reformate to anode
FC Anode to anode recuperator	45	4	Anode Exhaust to anode recuperator
Anode recuperator to POX	23	3	Anode recycle for POX
Anode HX to Tailgas burner	5	1	Anode exhaust (not recycled) to cathode oxid.
Tailgas burner to 2° Cathode recuperator	17	2	Tailgas burner exhaust
2° Cathode recuperator to Exhaust	4	1	Tailgas burner exhaust

Summary	
Total length, inches	284 (23.7 ft)
Number of pipe sections	29
Number of 90° elbows	33
Number of tees	2
Number of 45° elbows	3

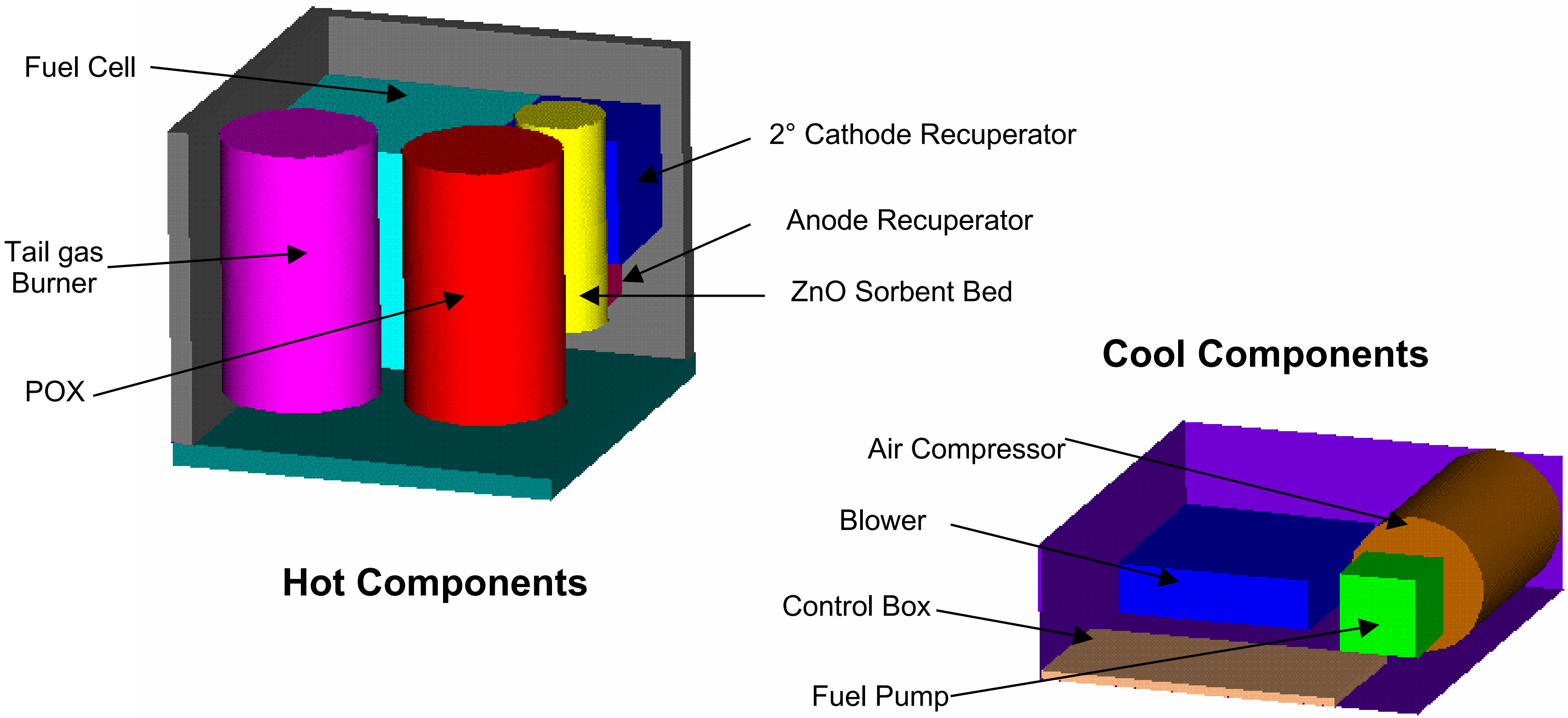
Notes:
1. In reality tubing diameter will vary ± 1/2
2. Internal manifolding is assumed for fuel cell stack.
3. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

One-inch tubing will connect the individual components together.

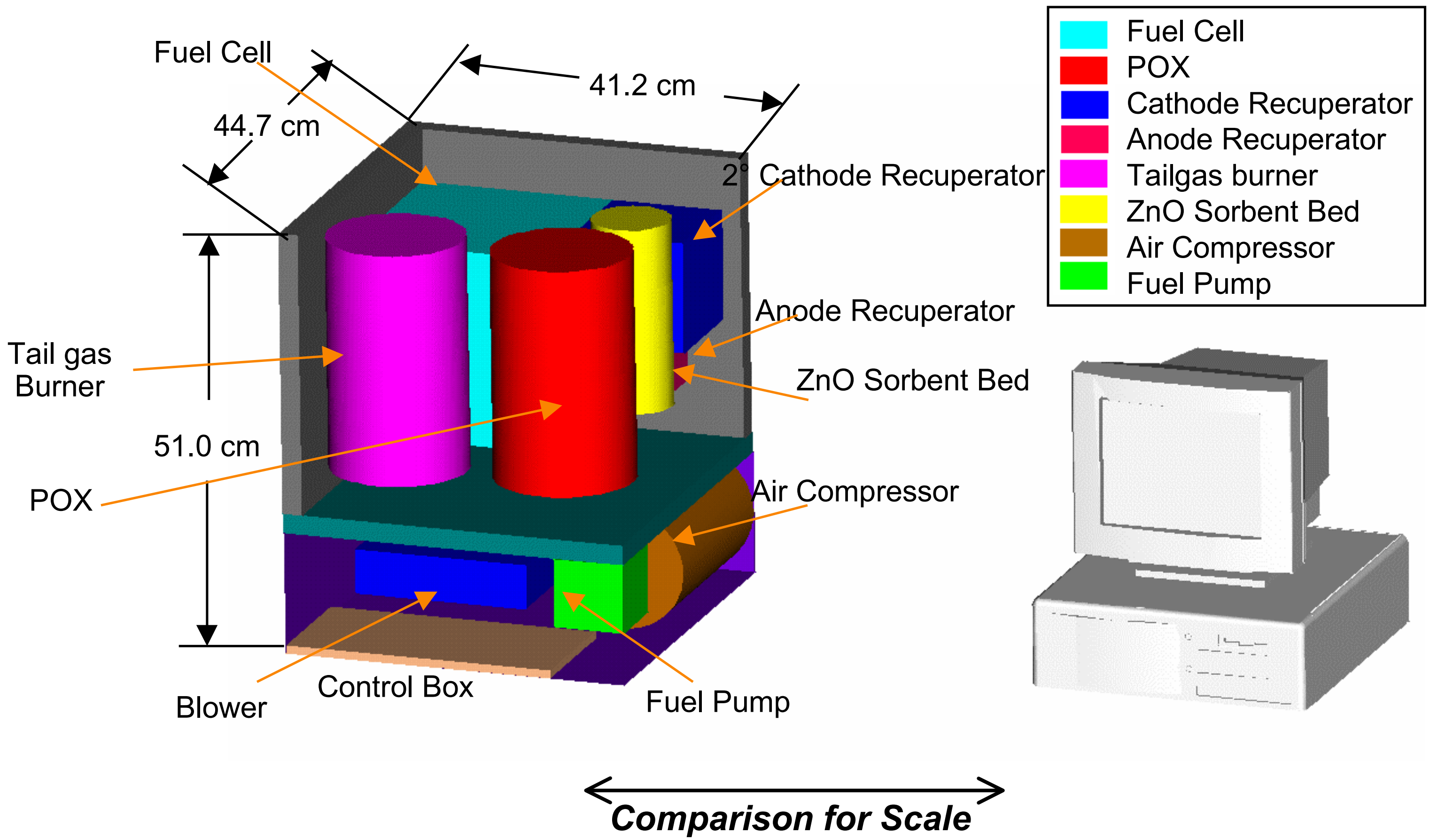


Note: NOT TO SCALE.

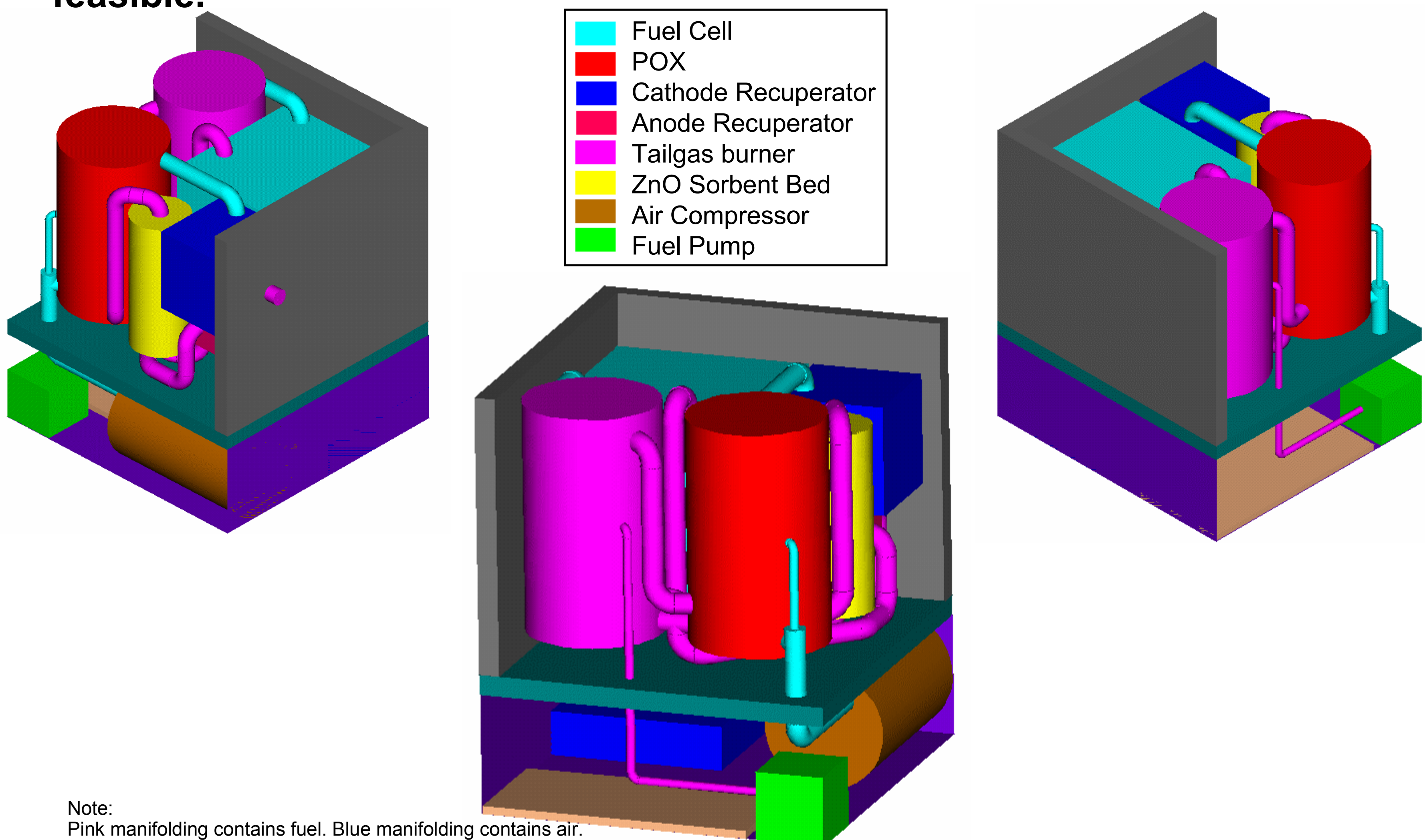
The hot and cool components will be kept apart in separate boxes.



In the first generation configuration, the hot component box and the cold component box have the same footprint.



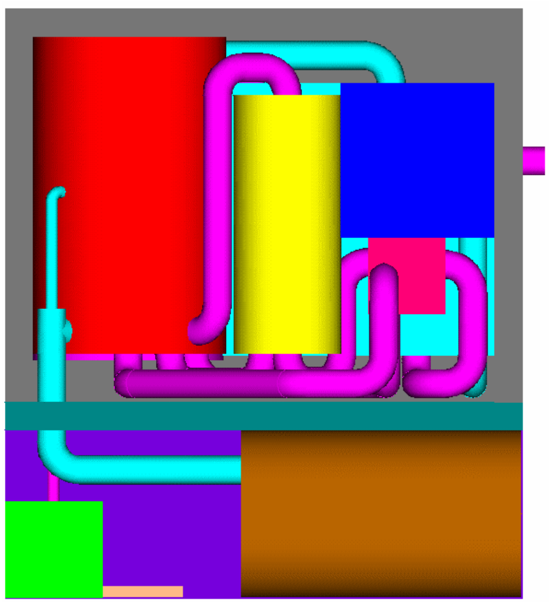
While the packaging of the first generation configuration is carefully designed, some further space savings in packaging are likely to be feasible.

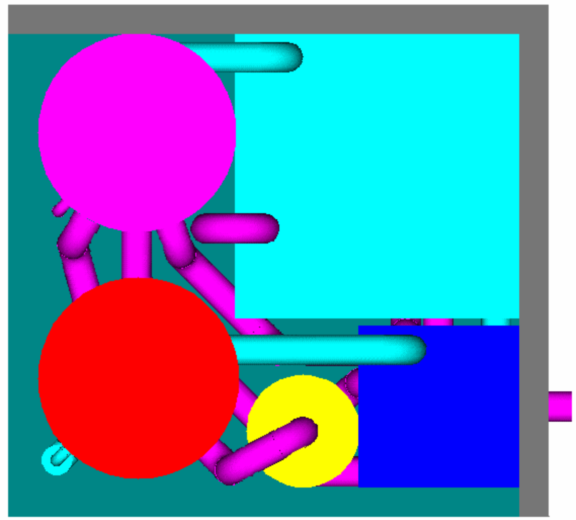


Note:
Pink manifolding contains fuel. Blue manifolding contains air.
The layout shown is for a first generation layout typically for a proof of system prototype. Commercial systems will likely incorporate further component integration.

1” piping will connect the individual components together.

Front View

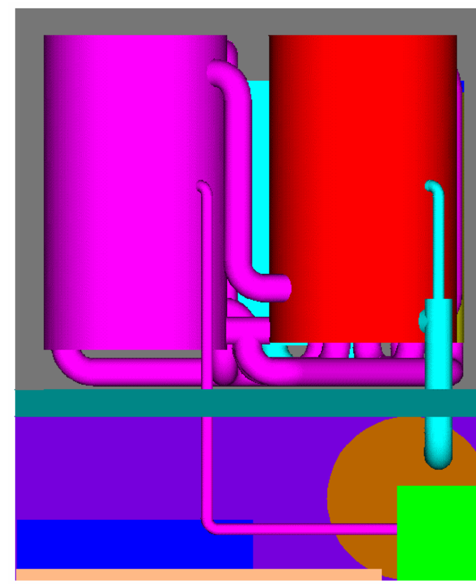




Top View

- Fuel Cell
- POX
- Cathode Recuperator
- Anode Recuperator
- Tailgas burner
- ZnO Sorbent Bed
- Air Compressor
- Fuel Pump

Side View



Note: Pink manifolding contains fuel.
Blue manifolding contains air.

Five separate cases were modeled to investigate the effects of different operating conditions and fuel type.

- Base Case
  - Realistic stack thermal management
  - Realistic power density
- Case 1 - Best Case Scenario
  - More aggressive stack thermal management assumptions
  - Assumes higher achievable power density
- Case 2 - Conservative Scenario
  - Conservative stack thermal management
  - Conservative fuel utilization of 70%
  - Assumes realistic power density
- Case 3 - Base case with higher achievable power density
- Case 4 - Sulfur free fuel
  - Similar assumptions as base case
  - Hexadecane as model Fischer-Tropsch Diesel fuel

We formulated five scenarios to bound the cost performance and the system volume estimates for POX/SOFC APU systems.

	Base Case	Case 1 Stretch	Case 2 Worst	Case 3 Basecase 0.6 W/cm^2	Case 4 Sulfur-free
Cathode Inlet Air Temperature	650 ºC	500 ºC	700 ºC	650 ºC	650 ºC
Anode H_2 Utilization	90%	90%	70%	90%	90%
Fuel	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	30 ppm S gasoline	0 ppm S Diesel
Single cell voltage	0.7 V	0.7 V	0.7 V	0.7 V	0.7 V
Power density, W/cm^2	0.3	0.6	0.3	0.6	0.3
Fuel cell gross rating, kW	6.02	5.53	6.97	6.02	6.04

The cost model contains both purchased components and manufactured components.

- The cost elements for the fuel cell stack contain raw material, processing, and capital recovery costs for a individual layer process flow manufacture scheme
- The cost elements for all other manufactured components include raw material and processing
- Remaining labor, indirect, and depreciation is included as a separate line item and is not distributed among the other manufactured components
- Raw material costs for system insulation and active cooling are included
  - Processing costs for system packaging are not included in analysis
  - Processing and labor for system assembly are not included
- Key purchased components include the compressor, fuel pump, blower, sensors, wiring, controllers, computer logic, and fittings

The manufactured components are estimated with a raw material cost and processing cost.

- The SOFC stack electrode-electrolyte assembly line item includes raw materials, processing, and associated labor, indirect and capital recovery costs
- The stack balance includes raw material and processing costs for the end plates, current collector, bolts and fuel cell packaging
- The reformer and Tailgas burner are rolled cylinders with stamped top/bottoms
  - The POX air preheater, vaporizer, and primary cathode air preheater are coils integrated into the vessels
  - In case 1, the secondary cathode air preheater is integrated in the Tailgas burner as a coil
- The anode recuperator and secondary cathode heat exchangers are treated as a coil encompassed with a shell
  - The shell is a rolled cylinder with stamped top/bottom
  - The coils are bent tubes
- The zinc sorbent bed is a rolled cylinder with stamped top/bottom
  - The cost also includes stamped mesh inserts and fittings to support the sorbent bed

Labor, indirect, and depreciation for the manufactured goods is kept as a separate line item.

The system cost for a 5kW net system ranges from $1754 to $3332.

Component Item, Total cost	Base case	Case 1	Case 2	Case 3	Case 4
Stack	***$1184***	***$595***	***$1369***	***$643***	***$1189***
◆ Electrode - Electrolyte Assembly (EEA)	$1088	$513	$1268	$560	$1092
◆ Stack balance components	96	82	101	83	97
Fuel and Air Preparation	***$433***	***$290***	***$734***	***$433***	***$296***
◆ POX reformer (+ preheaters)	109	109	114	109	107
◆ Tailgas burner (+ preheater & vaporizer)	42	59	46	42	42
◆ ZnO bed	50	50	50	50	n/a
◆ Anode gas recuperator	62	60	74	62	n/a
◆ Eductor	12	12	12	12	12
◆ Secondary cathode air preheater	158	n/a	439	158	135
Rotating Equipment	***$381***	***$276***	***$556***	***$381***	***$381***
◆ Fuel pump	109	109	109	109	109
◆ Air compressor and air filter	272	167	447	272	272
Balance of System	***$420***	***$410***	***$432***	***$402***	***$427***
◆ Insulation and channels	54	44	66	36	61
◆ Start-up and active cooling blower	78	78	78	78	78
◆ Controls and electrical	203	203	203	203	203
◆ Piping	85	85	85	85	85
Labor , indirect, & depreciation	215	181	240	215	167
Total, $	2636	1754	3332	2076	2461

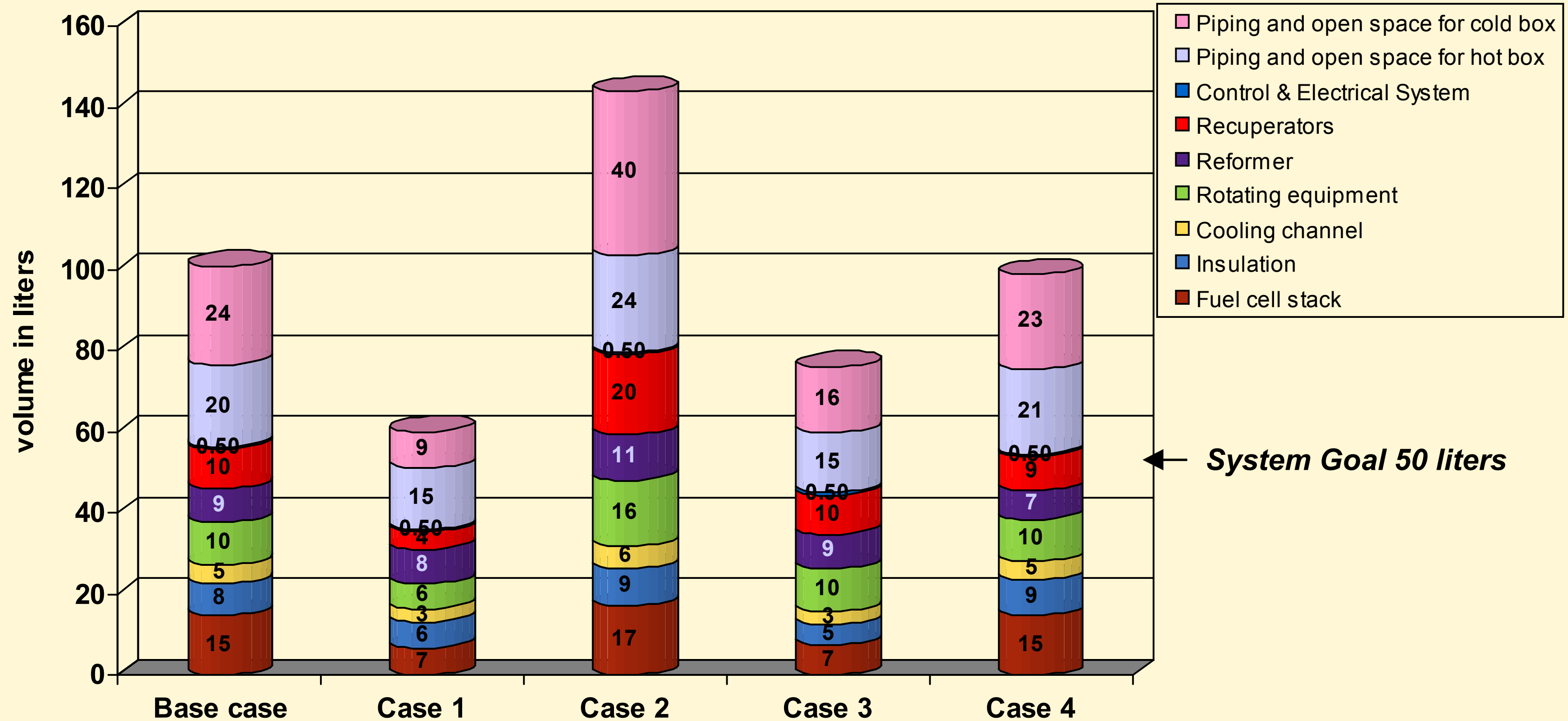
1. The fuel cell stack line items does not include insulation or external manifolding.
2. The fuel cell stack balance includes end plates, current collector, electrical insulator, outer wrap, tie bolts, FC temperature sensor, cathode air temperature sensor
3. The system insulation includes high and low temperature insulation and metal cost for manifolding of active cooling jacket
4. The fuel cell stack includes interconnects, anode, cathode, electrolyte, layer assembly, and final SOFC assembly
5. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

The system cost for a 5kW net system ranges from $351 to $666 / kW net.

Component Item, cost per kW (5 net)	Base case	Case 1	Case 2	Case 3	Case 4
Stack					
◆ Electrode - Electrolyte Assembly (EEA)	$217.6	$102.7	$253.6	$111.9	$218.4
◆ Stack balance components	19.3	16.4	20.2	16.6	19.3
Fuel and Air Preparation					
◆ POX reformer (+ preheaters)	21.8	21.8	22.7	21.8	21.4
◆ Tailgas burner (+ preheater & vaporizer)	8.5	11.8	9.2	8.5	8.5
◆ ZnO bed	9.9	9.9	9.9	9.9	n/a
◆ Anode gas recuperator	12.4	12.1	14.8	12.4	n/a
◆ Eductor	2.4	2.4	2.4	2.4	2.4
◆ Secondary cathode air preheater	31.7	n/a	87.7	31.7	26.9
Rotating Equipment					
◆ Fuel pump	21.8	21.8	21.8	21.8	21.8
◆ Air compressor and air filter	54.5	33.5	89.5	54.5	54.5
Balance of System					
◆ Insulation and channels	10.9	8.8	13.2	7.1	12.2
◆ Start-up and active cooling blower	15.7	15.7	15.7	15.7	15.7
◆ Controls and electrical	40.7	40.7	40.7	40.7	40.7
◆ Piping	17.0	17.0	17.0	17.0	17.0
Labor , indirect, & depreciation	43.0	36.2	48.0	43.0	33.4
Total, $	527	351	666	415	492

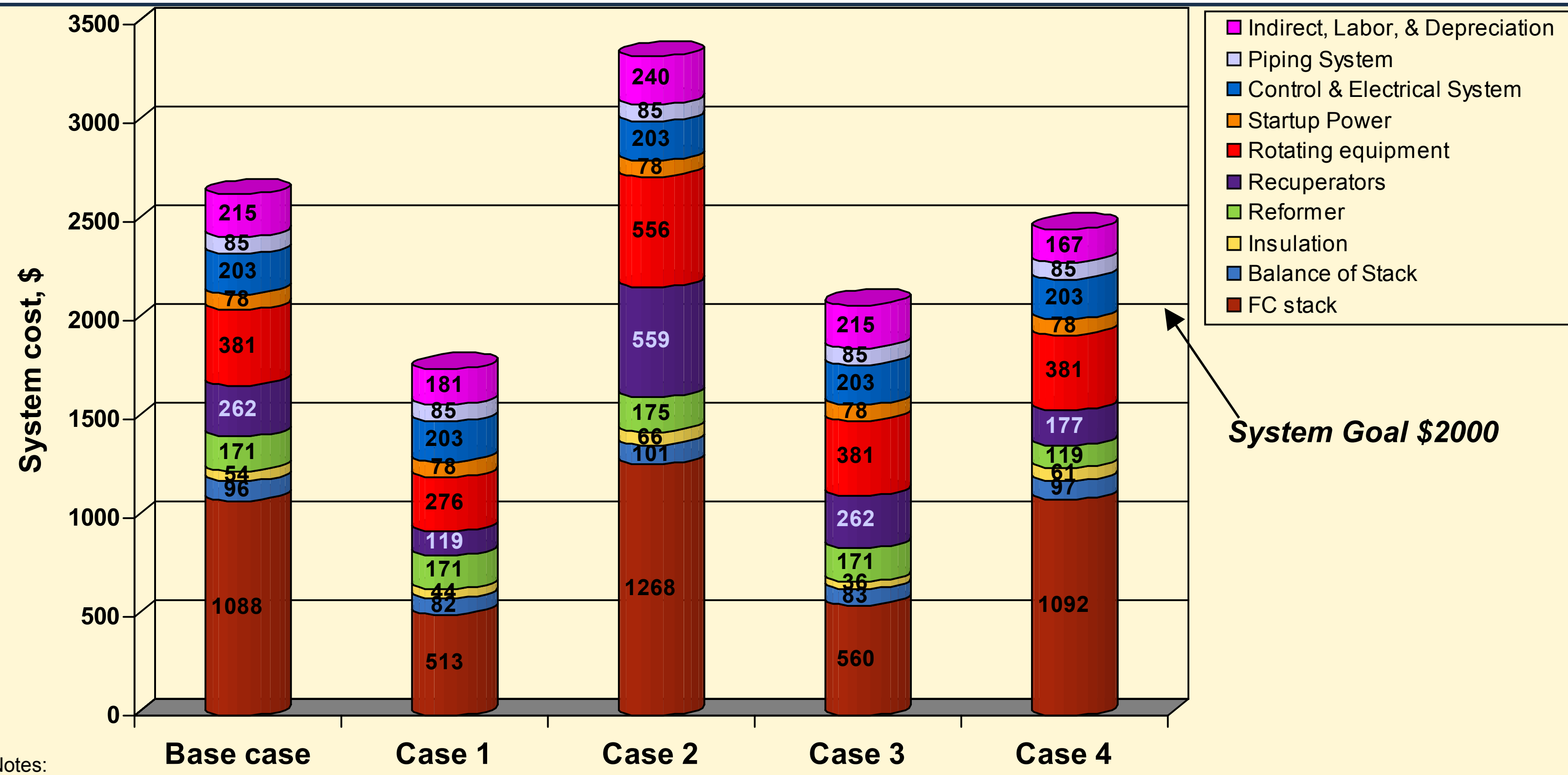
1. The fuel cell stack line items does not include insulation or external manifolding.
2. The fuel cell stack balance includes end plates, current collector, electrical insulator, outer wrap, tie bolts, FC temperature sensor, cathode air temperature sensor
3. The system insulation includes high and low temperature insulation and metal cost for manifolding of active cooling jacket
4. The fuel cell stack includes interconnects, anode, cathode, electrolyte, layer assembly, and final SOFC assembly
5. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Sufficient stack power density and thermal management are required to approach the volume target of 50 liters (results were 60 to 145 liters).



Notes:
1. The fuel cell stack line items does not include insulation or external manifolding.
2. The system insulation includes high and low temperature insulation
3. The reformer includes volume for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
4. The recuperators include the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
5. Rotating equipment includes the air compressor, fuel pump, and air blower for active cooling
6. The anode preheater and the secondary cathode air exchanger are configured as compact finned cross flow cube heat exchangers
7. In the base case, assuming all the volume of manifolding is in the hot box, the 20 liters includes 14.6 liters of piping for 5.4 liters of open space in the base case hot box.
8. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.
9. Thermal management of the stack determines the amount of excess cathode air needed for cooling which in turn, impacts parasitic power.

Target system costs appear achievable with high power density; the fuel cell stack cost represents 27 to 44% of the system cost.



Notes:
1. The fuel cell stack cost does not include protective conductive coatings on the metallic interconnect, which if needed, could increase stack costs by 5-10%.
2. The fuel cell stack line items does not include insulation or external manifolding.
3. The fuel cell stack balance includes end plates, current collector, electrical insulator, outer wrap, tie bolts, FC temperature sensor, and cathode air temperature sensor
4. The system insulation includes high and low temperature insulation and metal cost for manifolding of active cooling jacket
5. The reformer includes cost for the POX reformer, POX air preheater, the primary cathode air preheater and the zinc bed (except for case 4)
6. The recuperator includes the Tailgas burner, vaporizer, primary and secondary cathode air preheaters and the anode preheater (except in case 4)
7. Rotating equipment includes air compressor and fuel pump
8. Startup power includes cost for battery and active cooling blower
9. Indirect, Labor, and Depreciation includes all indirect costs, labor costs, and depreciation on equipment, tooling, and buildings
10. The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Fuel cell stack cost and performance are the most significant cost drivers for 5kW auxiliary power unit SOFC systems.

- Increasing the power density from 0.3 W/cm^2 to 0.6 W/cm^2 saves $112/kW assuming similar system efficiency
- Increasing the approach temperature of the cathode air and the stack from 150°C to 300°C saves $64/kW
  - Larger approach temperatures result in lower cathode air cooling requirements
  - Smaller cathode air cooling requirements translates into smaller recuperator and smaller parasitic loads
- Poor stack performance and thermal management can result in a penalty of $139/kW compared with base case performance
  - Poor stack performance increases reformer requirements
  - Poor stack thermal management results in high cathode excess air requirements and higher parasitic loads
- The cost impact of using low/no sulfur fuel can save $35/kW from simpler system configuration

The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Stack thermal management and power density are critical issues impacting the cost and performance of reformer/planar SOFC systems.

	How can reformer / planar SOFC systems be applied to truck APUs and how much will they cost?		
	System Performance[1]	**Cost**	**Volume & Weight**
Internal Stack Thermal Management[2]	●	●	●
Power density / Operating Voltage	●	●	●
Stack Fuel Utilization	●	◒	◒
Stack Thermal Mass[3]	●	○	○
Recuperator	○	●	●
Parasitic power	◒	●	●
Reformer efficiency	◒	◒	◒
Insulation	○	○	●

● Critical ◒ Important ○ Not Leveraging

1. System performance refers to e.g. system efficiency, start-up and shut-down time.
2. Stack thermal management refers to the maximum thermal gradients allowable and degree of internal reforming possible at anode.
3. Critical if provisions must be made to meet tight start-up specifications.

Stack thermal management directly impacts recuperator and parasitic requirements and system volume.

System efficiency targets can be met under most circumstances but heat-up time targets are unrealistic without further technology improvements.

- System efficiency of greater than 35% is easily achievable[1]:
  - Typical efficiency 37%
  - 40% efficiency appears achievable (even at this scale)
  - Stack thermal management can significantly impact efficiency
- Use of sulfur free fuel does not dramatically change system performance or cost from base case sulfur containing fuel operation
  - Alternative reforming technologies such as steam reforming or fully internal reforming were not considered
  - The sulfur free fuel case represents a conservative impact of possible sulfur-free alternative fuels
- A 10 minute start-up time appears unrealistic with current technology:
  - Thermal mass of stack would require significant additional heating and air movement capacity, with significant size (30%) and cost (15%) penalties
  - Materials thermal shock resistance issues will further increase start-up time
  - Minimum practical start-up times from a system perspective is about 30 minutes
  - Heat-up time will also be dependent upon sealing technology used for stack

1. The system efficiency was set by a using a 0.7 Volt unit cell voltage, a POX reformer, and required parasitics. Higher efficiency is achievable at higher cost by selecting a higher cell voltage

Our analysis indicates that achieving the 50-liter volume target will be challenging without further improvements in stack technology.

- System volume estimates range from 60 to 145 liters[1].
- The balance of plant represented by the reformer, recuperators, and rotating equipment represent the largest fraction of the physical equipment
- The actual fuel cell stack and insulation volume occupies between 24-31% of the total system volume
- For the first generation system layout, the largest single volume element was spacing between the components to account for manifolding
- Aggressive stack thermal management and internal reforming will have the greatest impact on volume reduction by impacting the size of required heat recuperators
  - Decrease cathode air requirement
  - Allow more component integration
  - Decrease manifolding and insulation requirements
- Some savings may be obtained by closer packing of rotating equipment and controls and further overall component integration and optimized layout

The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Achieving the $400/kW system cost target appears feasible with high power density stack performance and good stack thermal management.

- System cost estimates range from $351 to $666 per kW for 5 kW SOFC APU systems
- Fuel cell stack cost and balance of plant (reformer and recuperators) are the key cost drivers for the 5kW net system
- As achievable power density increases, the cost of purchased components such as rotating equipment becomes a key cost driver
- Increasing the power density from 0.3 W/cm^2 to 0.6 W/cm^2 saves $112/kW assuming similar system efficiency
- Aggressive stack thermal management could save $64/kW while poor stack performance and thermal management can result in a penalty of $139/kW
  - Aggressive stack management reduces recuperator area and air movement requirements
- Using low/no sulfur fuel can save $35/kW from simpler system configuration (not considering alternative reformer technology)
  - A zinc sulfur removal bed is not required
  - An anode recuperator is not required

The absolute error of the estimate is 30-40 percent. Comparison among the cases is more accurate, approximately 5-10 percent.

Performance, cost, and size of planar SOFCs offer significant opportunity in a wide range of applications.

- Estimated performance and cost appear:
  - Very competitive for APUs and distributed generation technologies
  - Very attractive for stationary markets
- Performance, size and weight may have to be further improved for key transportation markets
- The impact of lower volume production must be considered for some markets
- The impact of system capacity (modules of 5kW stacks units) should be considered for larger-scale applications
- First order risk exists in that publicly available information of a stack demonstration of a planar anode supported architecture operating at 650-800°C does not exist