Planar POX/SOFC Design

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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.

Objective

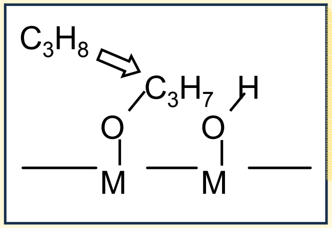
DOE/NETL/SECA asked Arthur D. Little to develop a conceptual design package and cost estimate for a planar anode supported SOFC system.

System Performance	Physical Characteristics	System Cost Targets
◆ Efficiency greater than 35% at peak power (LHV) ◆ Rating, 5 kWe net ◆ Operating life greater than 5000 hours ◆ Cold (25°C) start-up time < 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

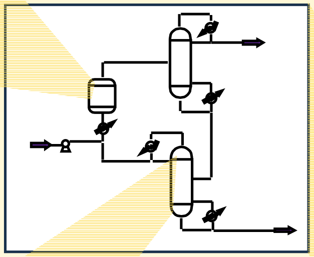
The target application for this module is an auxiliary power unit (APU) for on-road vehicles such as trucks.

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

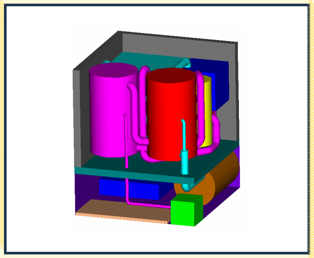
Fuel Cell Performance & Cost Model



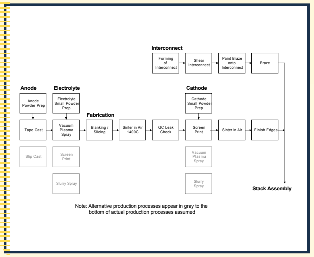
Reformer model



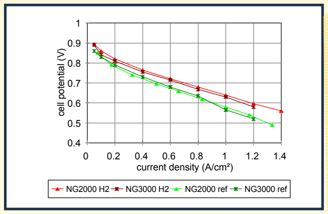
Thermodynamic System Model



Conceptual Design and Configuration



Manufacturing Cost Model



Fuel Cell Model

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

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

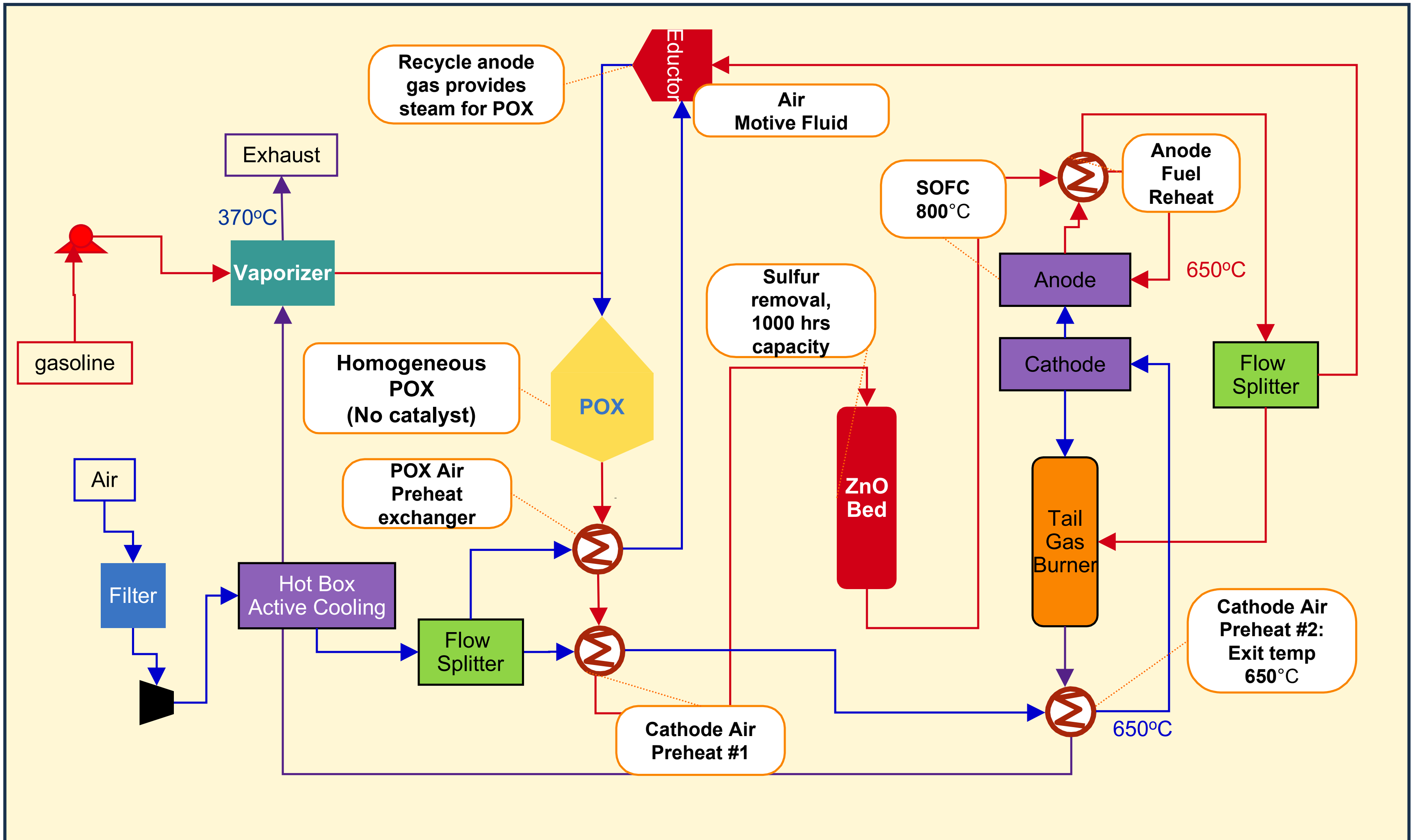
1. The reformer also incorporates the POX air preheater, primary cathode air preheater, air/fuel/recycle mixer, and eductor integrated inside.
2. The Tailgas burner incorporates the fuel vaporizer, and in case 2 the secondary cathode air preheater integrated inside.
3. The fuel cell stack includes cathode, 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 assumptions about operating conditions and fuel type.

	Base Case	Case 1 Improved Stack Performance	Case 2 Poorer Stack Performance	Case 3 Higher Power Density	Case 4 Sulfur-free Diesel Fuel
Cathode 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].

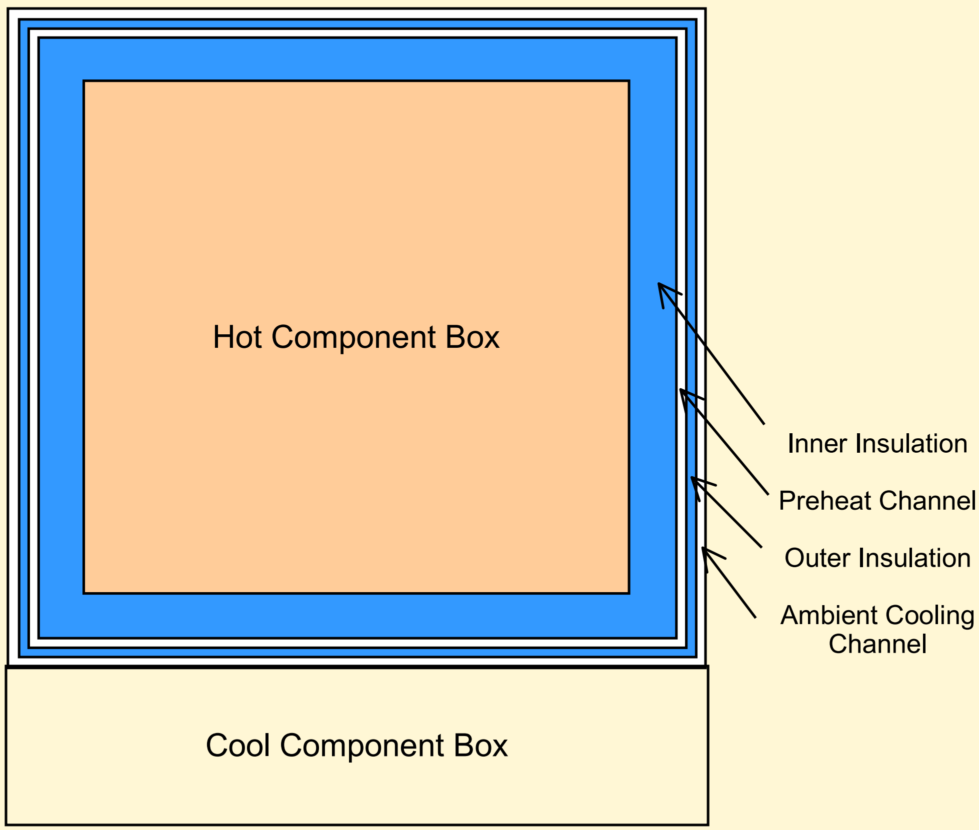
	Base Case	Case 1	Case 2	Case 3	Case 4
Anode Fuel Utilization	90%	90%	70%	90%	90%
Fuel Cell Efficiency[3]	49%	49%	38%	49%	49%
POX Effluent Temperature	890ºC	890ºC	940ºC	890ºC	910ºC
Estimated POX (with recycle) Efficiency[1]	87%	87%	91%	87%	87%
Cathode Inlet Air Temperature	650ºC	500ºC	700ºC	650ºC	650ºC
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.



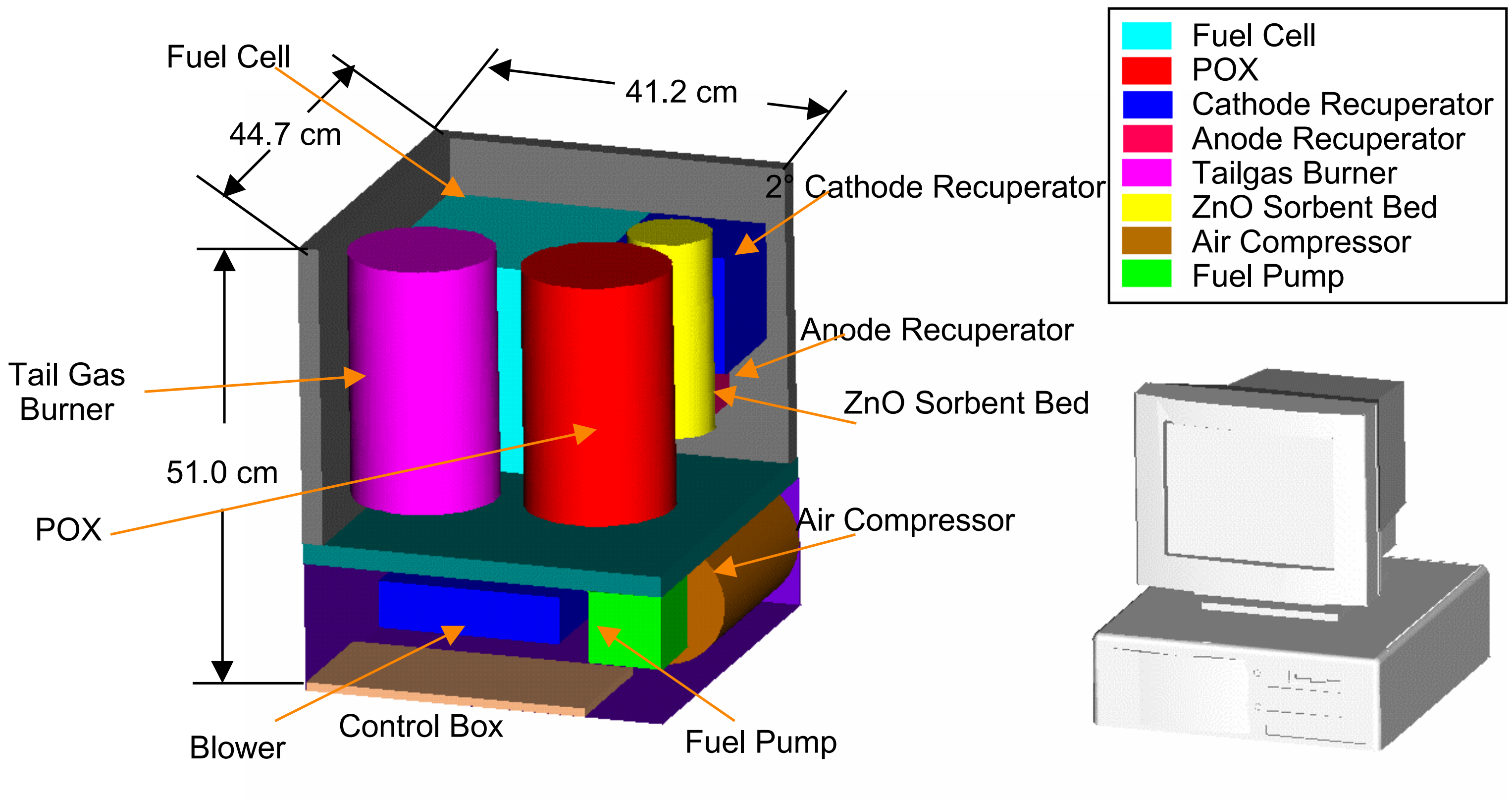
Hot Component Box:

- 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.

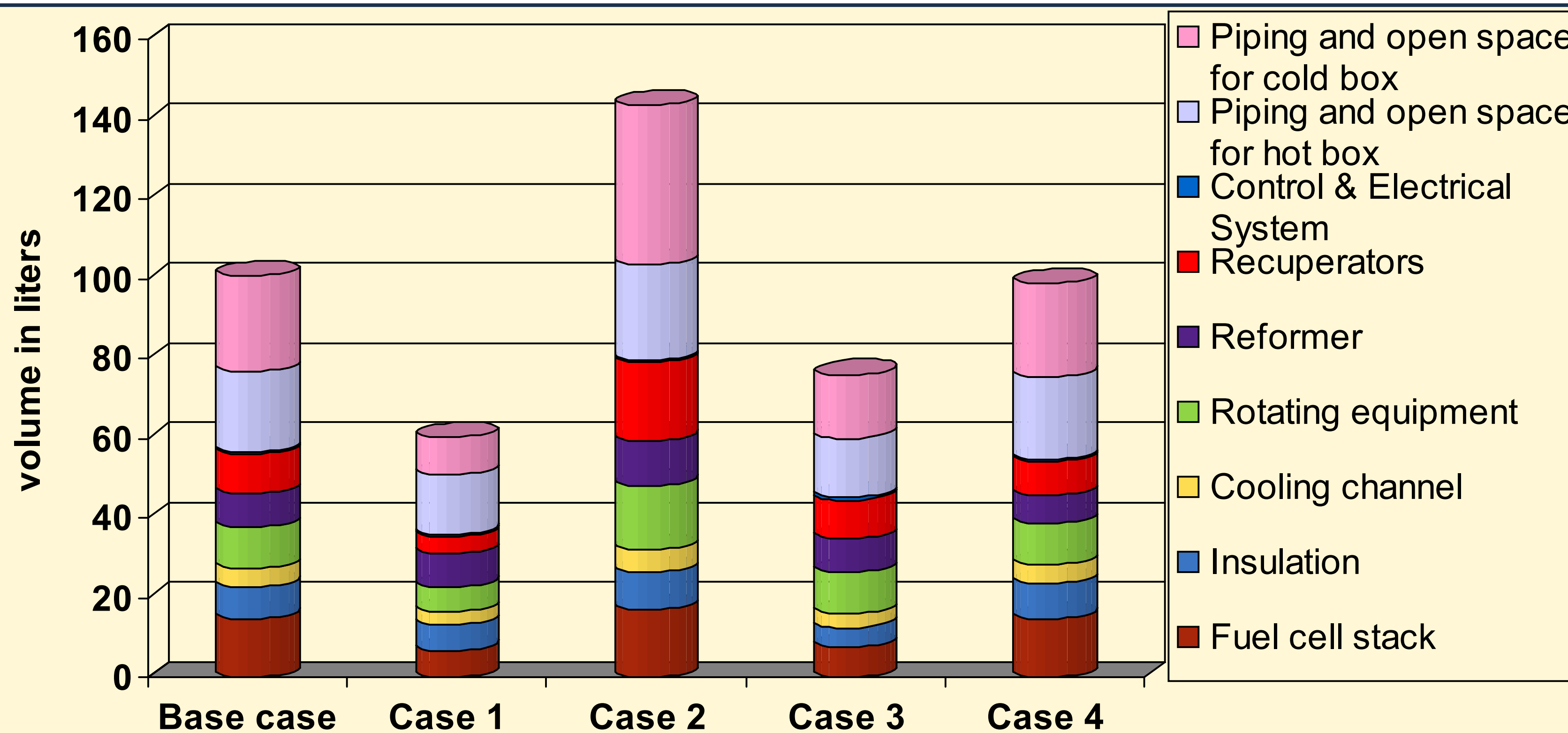


System package volume 94 liters

Comparison for Scale

Volume Estimates

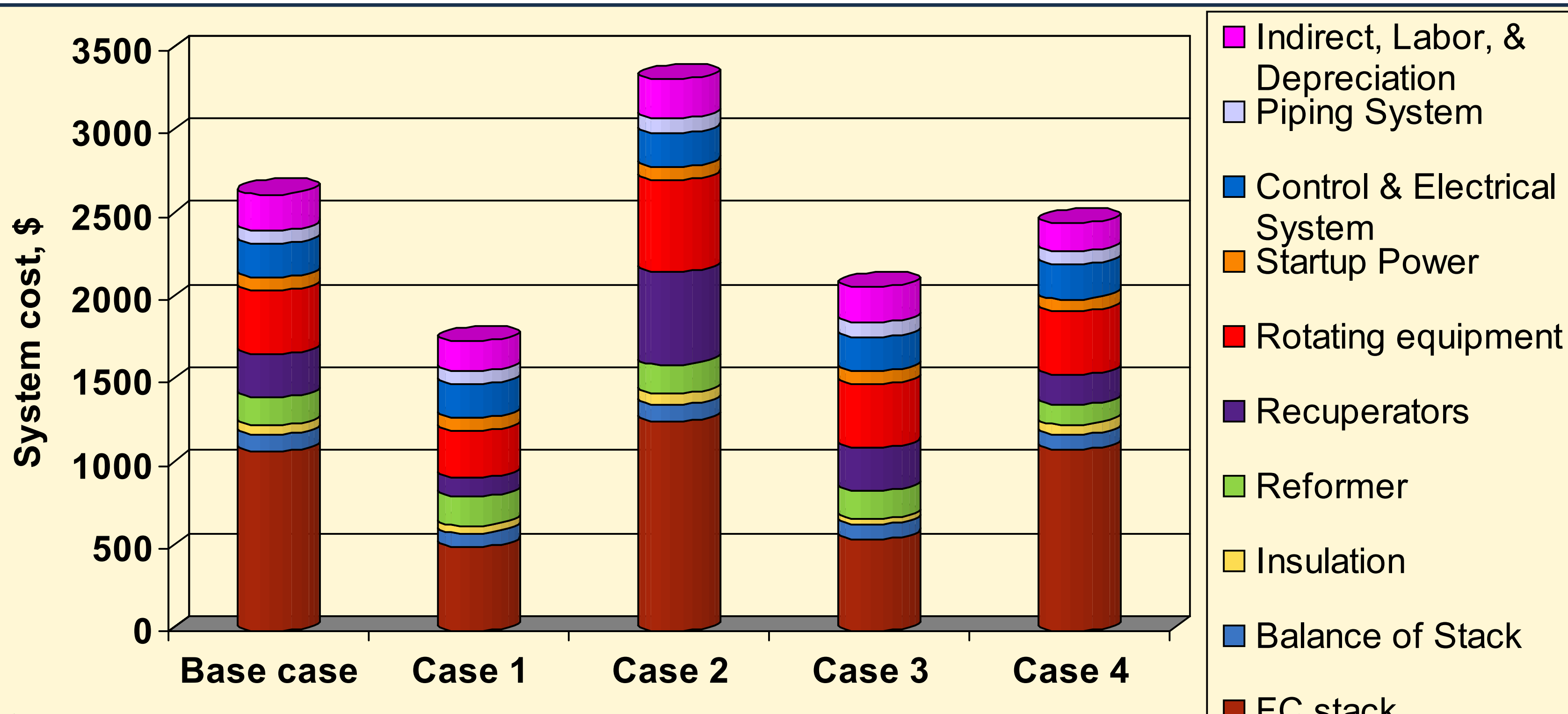
Sufficient stack power density and thermal management are required to approach the volume target of 50 liters (results were 60 to 145 liters).



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.

A system cost of $2500 or less (or $500/kW) appear achievable; 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.

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.

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