Scale-up study of 5-kW SECA modules to a 250-kW system

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Final Report

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Report Topics

NETL would like to understand if and how SECA's SOFC stack technology could be used in larger power plants, such as NETL's Vision 21 plants.

- The Vision 21 power plant is a concept of a virtually pollution-free energy plant providing a variety of products: power, heat, fuels and chemicals
  - Capable of a wide variety of fuels such as coal, natural gas, biomass, petroleum coke and municipal waste
  - Carbon sequestration capability for little greenhouse gas emissions
  - High electrical efficiency of 60% for coal; 75% for natural gas (LHV)
- The SECA vision is to create a solid oxide fuel cell modular technology (3 to 10-kW) that can be mass produced and used in numerous applications
  - Broad use in transportation, distribution generation and military applications
  - Efficient at lower capacity, 40-60% efficiency in individual electric systems and up to 80% in hybrid systems
  - Fuel flexible – Uses available liquid fuels such as gasoline and diesel as well as natural gas and propane
- Despite the obvious potential synergy between these programs, it is not clear how kW-scale SECA modules would be scaled-up to MW-scale systems

SECA would like to understand the issues of scaling up 5-kW planar SOFC systems to higher capacity applications of 100-kW to 1-MW.

Application of stack modules to larger capacity applications is key to SECA's strategy.

- Develop nominal 5-kW planar SOFC modules for mass-customization
- Small-capacity applications (using 1 to 5 stacks), including:
  - Residential / light commercial distributed generation (DG)
  - Auxiliary power for vehicles
  - Remote power
- Larger capacity applications:
  - Large commercial / industrial DG (10 to 1000's stacks)
  - Sub-station level DG and central generation (synergy with NETL Vision21 program)
- The key question is how to scale-up to hundreds of kW or MW?

SECA wanted to understand the issues involved in scaling up to 100-kW to 1-MW systems.

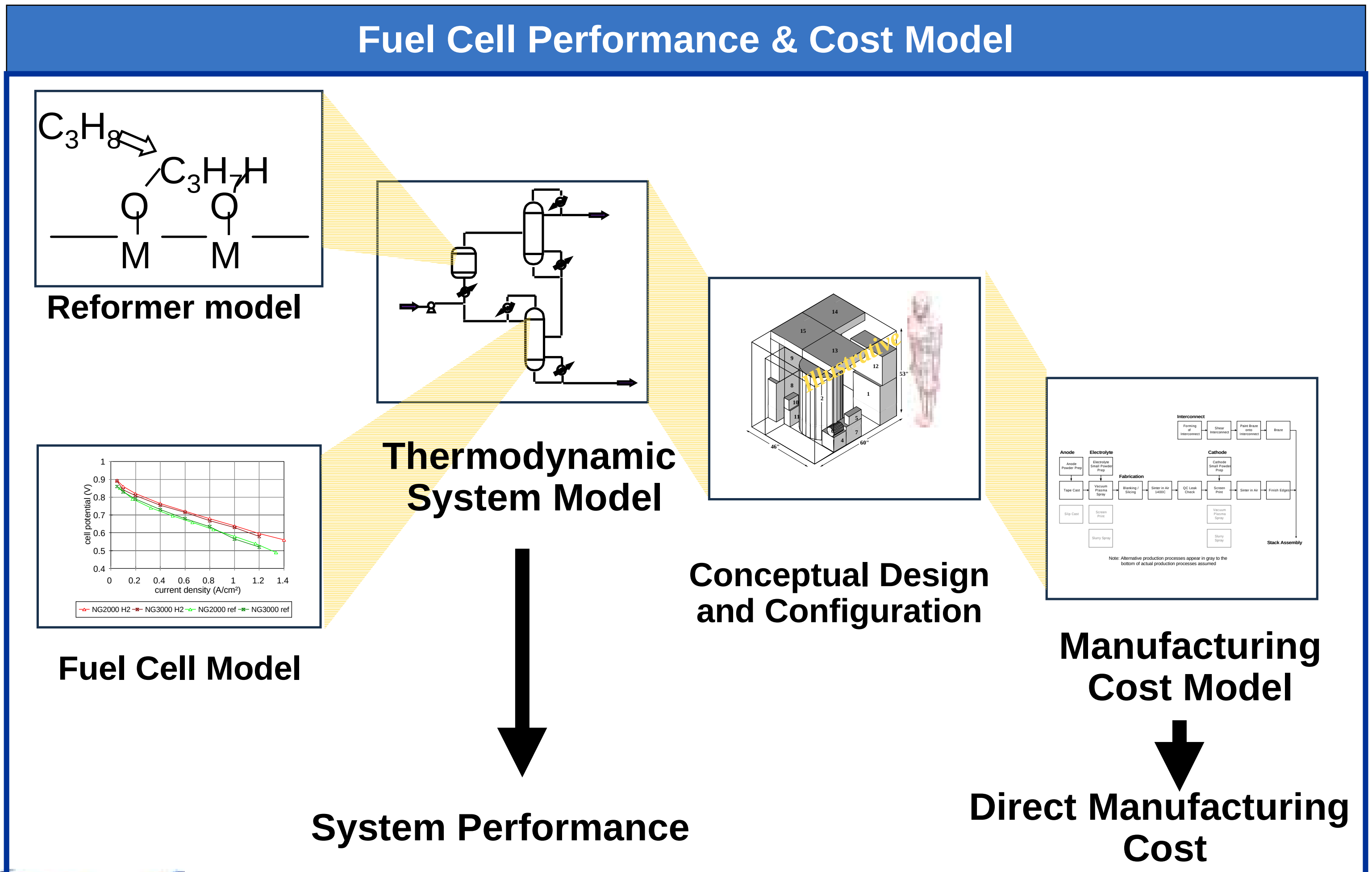
The objective of the study was to assess whether and how SECA stack modules can be integrated into a 250-kW_e plant.

- Develop thermodynamic design, system lay-out, performance estimate, and cost estimates
- SOFC stack:
  - Use 5-kW planar SOFC modules
  - Combine into super-modules
  - What are the implications for electric interconnection of the units?
  - What are the implications for manifolding?
- Balance of plant:
  - Determine scale and integration
  - What is impact of scale-up on system performance and cost?
- Simple-cycle operation
  - Combined cycle operation was not part of the scope of this study

We developed a conceptual design for a 250-kW$_e$ distributed generation system SOFC.

System Specifications	Assumptions: Stack	Assumptions: Balance of Plant
◆ System output: 250-kWe net @ 380V 3-phase AC ◆ Electrical system efficiency goal >50% (LHV) ◆ Availability goal >99% ◆ TSurface< 45°C ◆ High production volume (10,000 250-kW units per year)	◆ 5-kW modules ◆ Cell voltage 0.7 V ◆ Anode-supported technology ◆ T_{stack} 650 - 800°C ◆ Power density 0.6 W/cm^2 ◆ 85% fuel utilization per pass in fuel cell	◆ Water supplied (no water recovery) ◆ Steam reformer ◆ Natural gas fuel, (20" H_2O gauge)

We used a multi-level modeling approach to develop direct manufacturing cost estimates for the system.



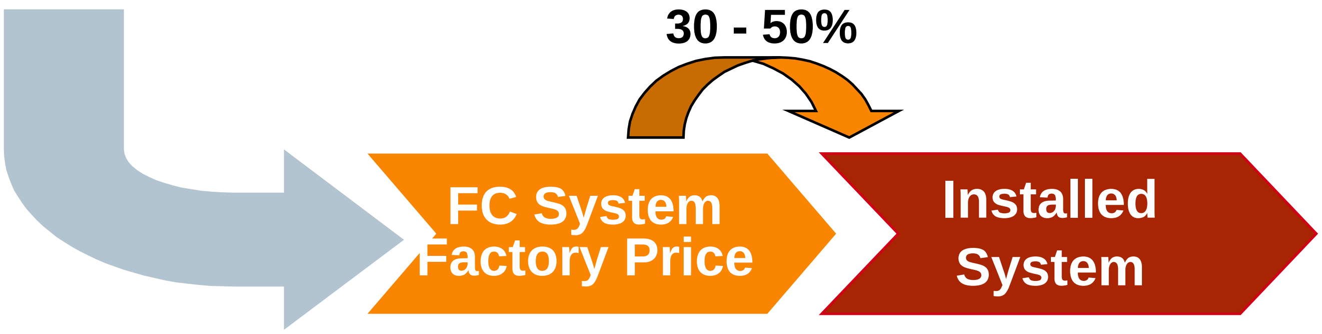
To estimate installed cost, value-chain mark-up and installation cost must be added.

Direct Manufacturing Cost

+

Factory Profit & Overhead

- Profits
- Sales costs
- General overhead
- R&D cost



The cost model contains both purchased components and manufactured components.

Purchased Components

- Air blowers
- Natural gas compressor
- Water pump
- Air and fuel filters
- Control and solenoid valves
- Controllers for rotating equipment, processors and hardware
- Piping, fittings & connectors
- Thermocouples/sensors
- Wiring for sensors & valving
- Insulation (high and low temperature)

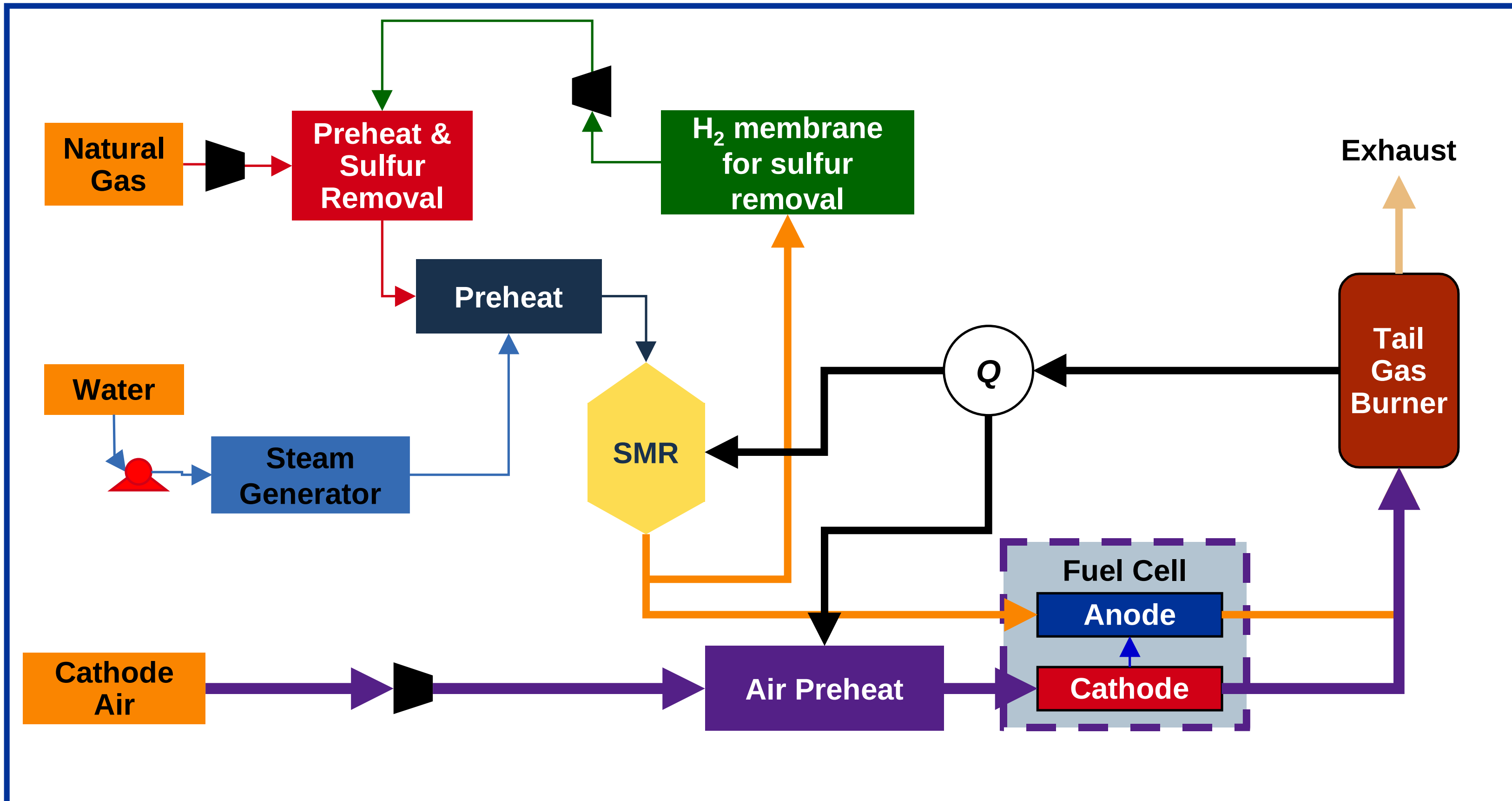
Manufactured Components

- Fuel cell stack
- Fuel cell stack hardware
- Fuel cell packaging
- Recuperators
- Zinc bed
- Steam reformer

Raw Materials

- Steel sheet
- Metal foil
- Chemicals
- Nickel oxides

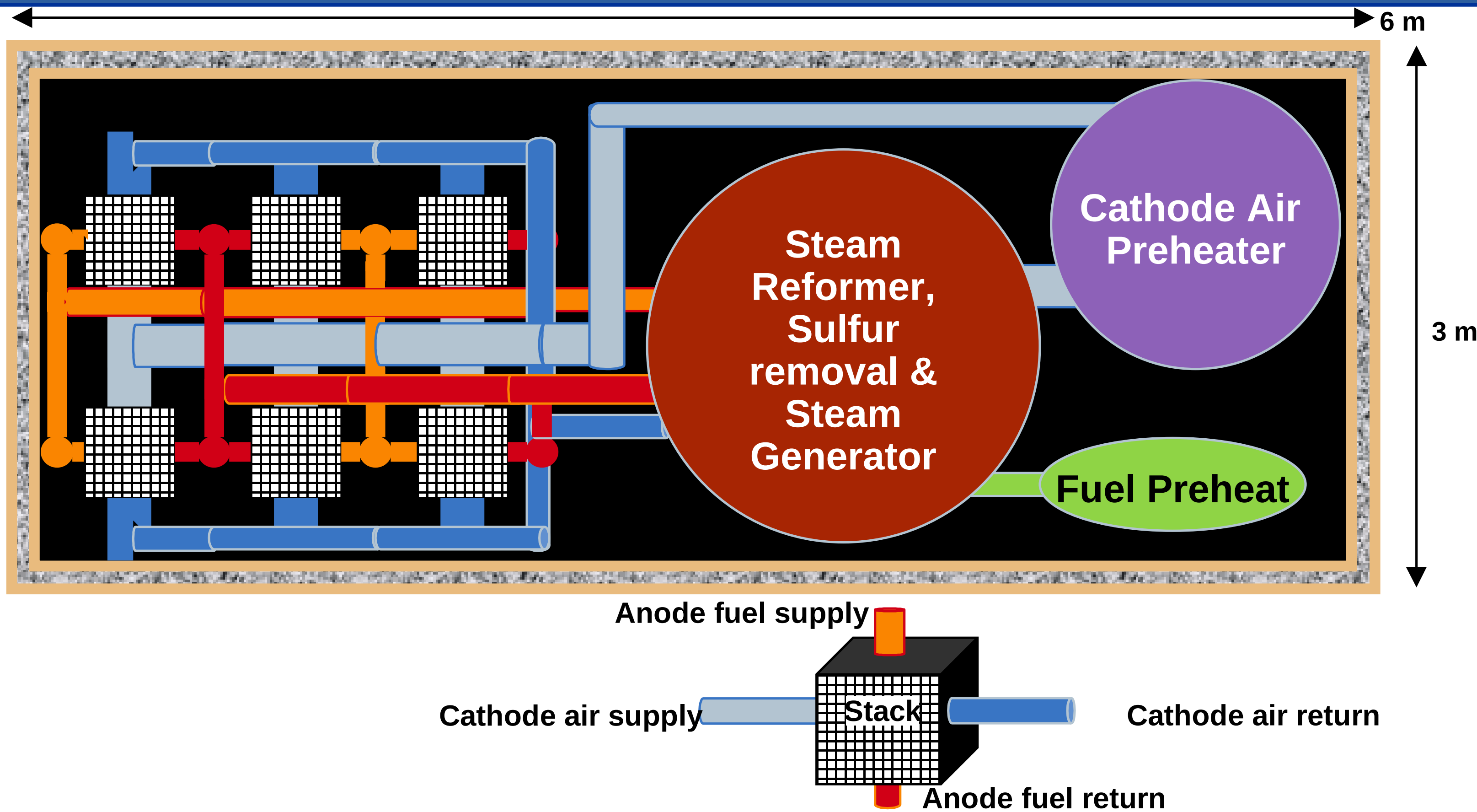
Use of a steam methane reformer (SMR) offers opportunities for tight thermal integration.



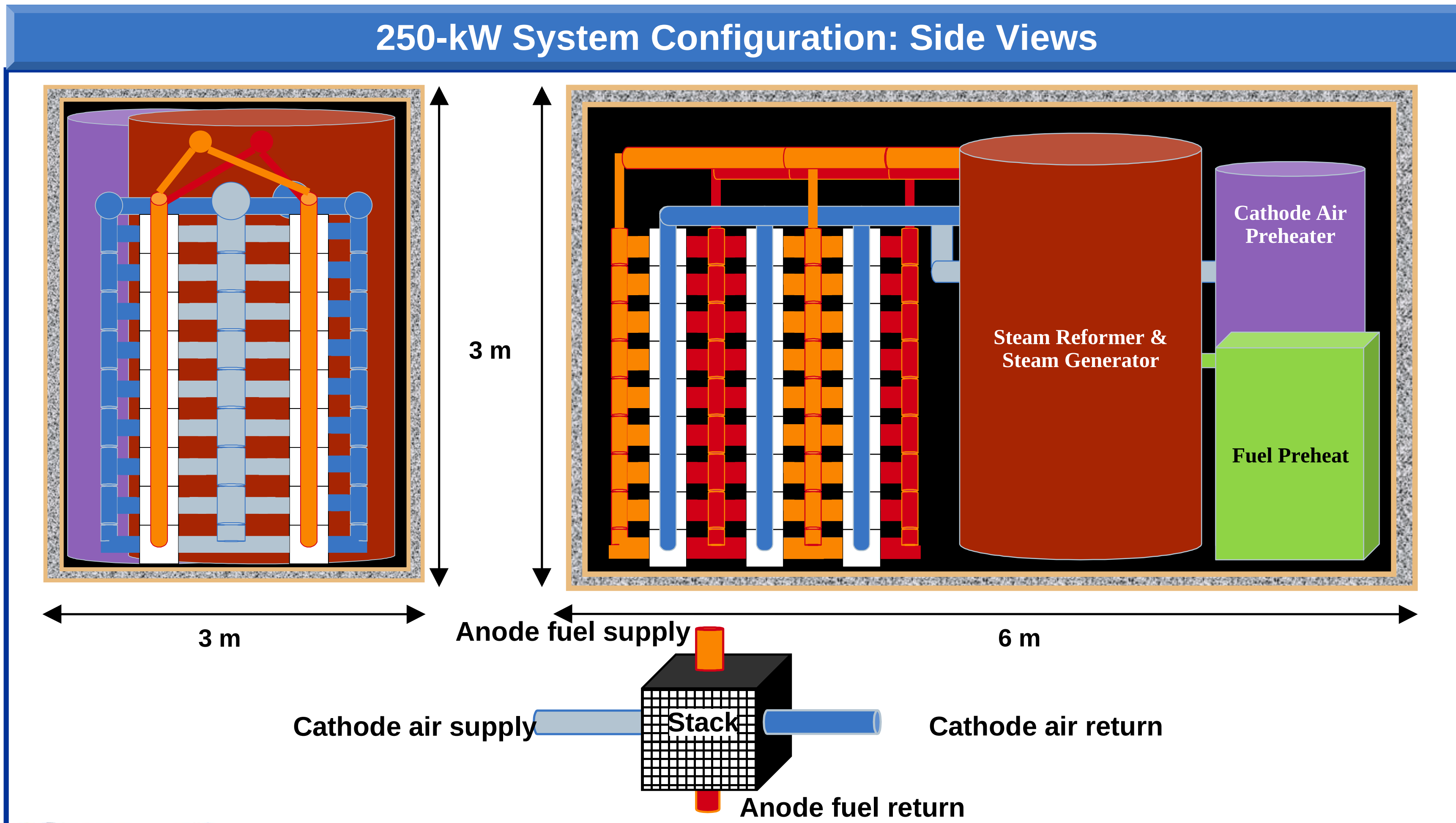
Unconverted anode exhaust provides fuel (and energy) to drive the endothermic reactions of the SMR.

We developed a conceptual system design, to assess implications of manifolding and equipment interconnection.

Hot Box Configuration with Rectangular Cross-Flow Cells: Top View

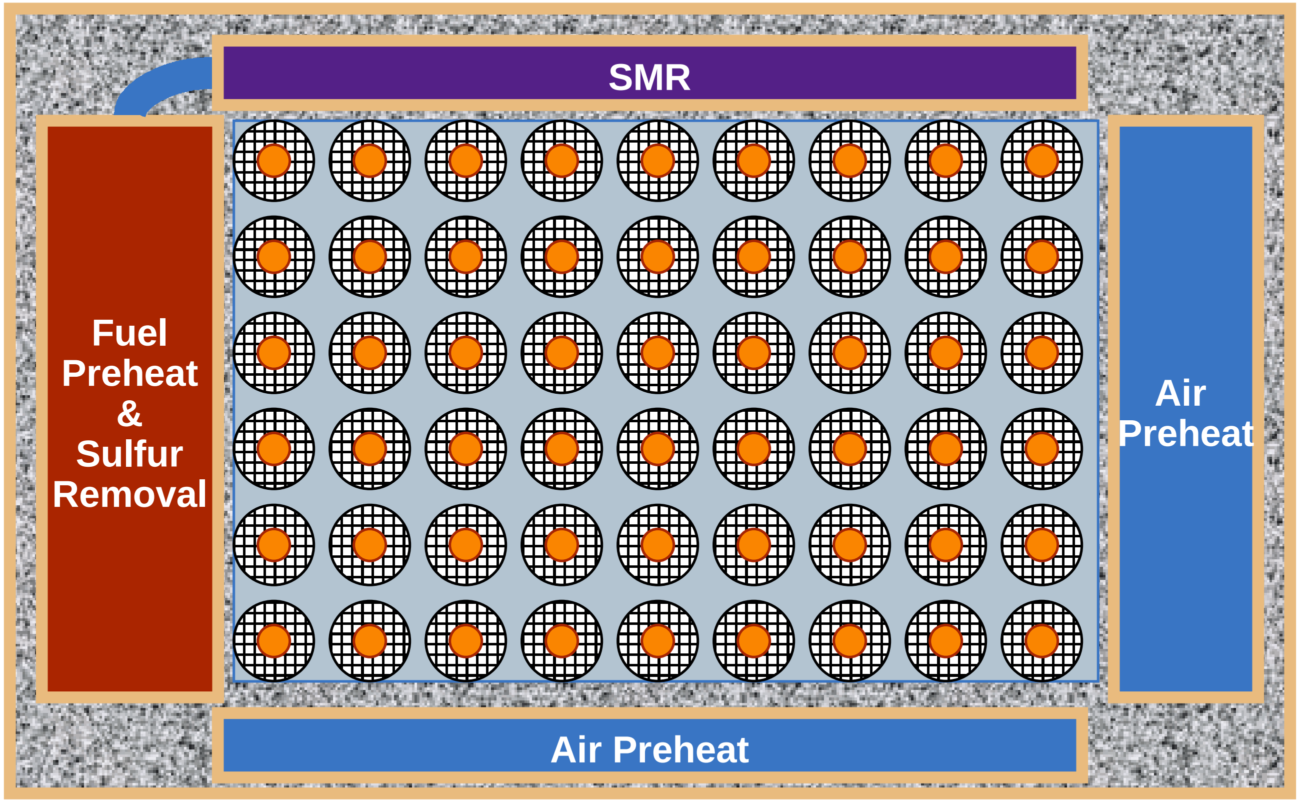


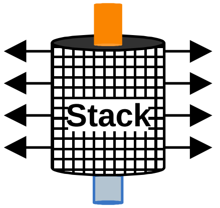
We limited integration to the reformer and air preheater, to maintain reasonable access.



With cylindrical stacks, a simpler manifolding arrangement may be feasible...

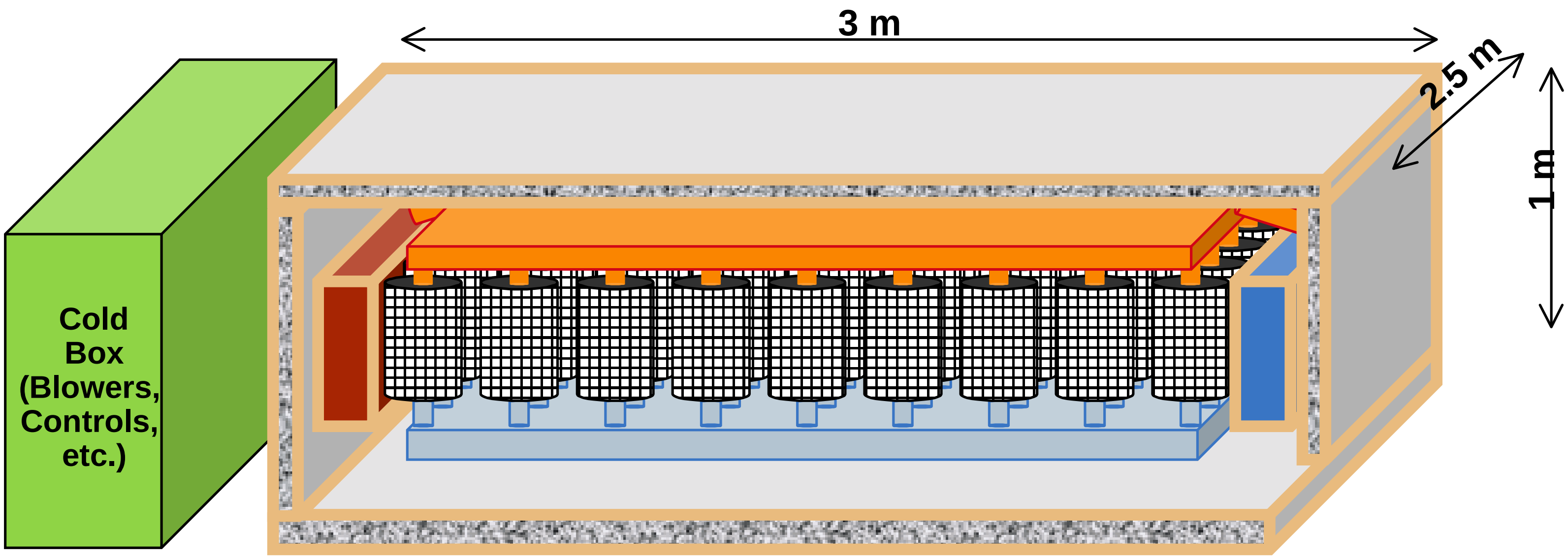
Hot Box Configuration with Radial-Outflow Cells: Top View





… and a more compact overall design.

Hot Box Configuration with Radial-Outflow Cells: Side View

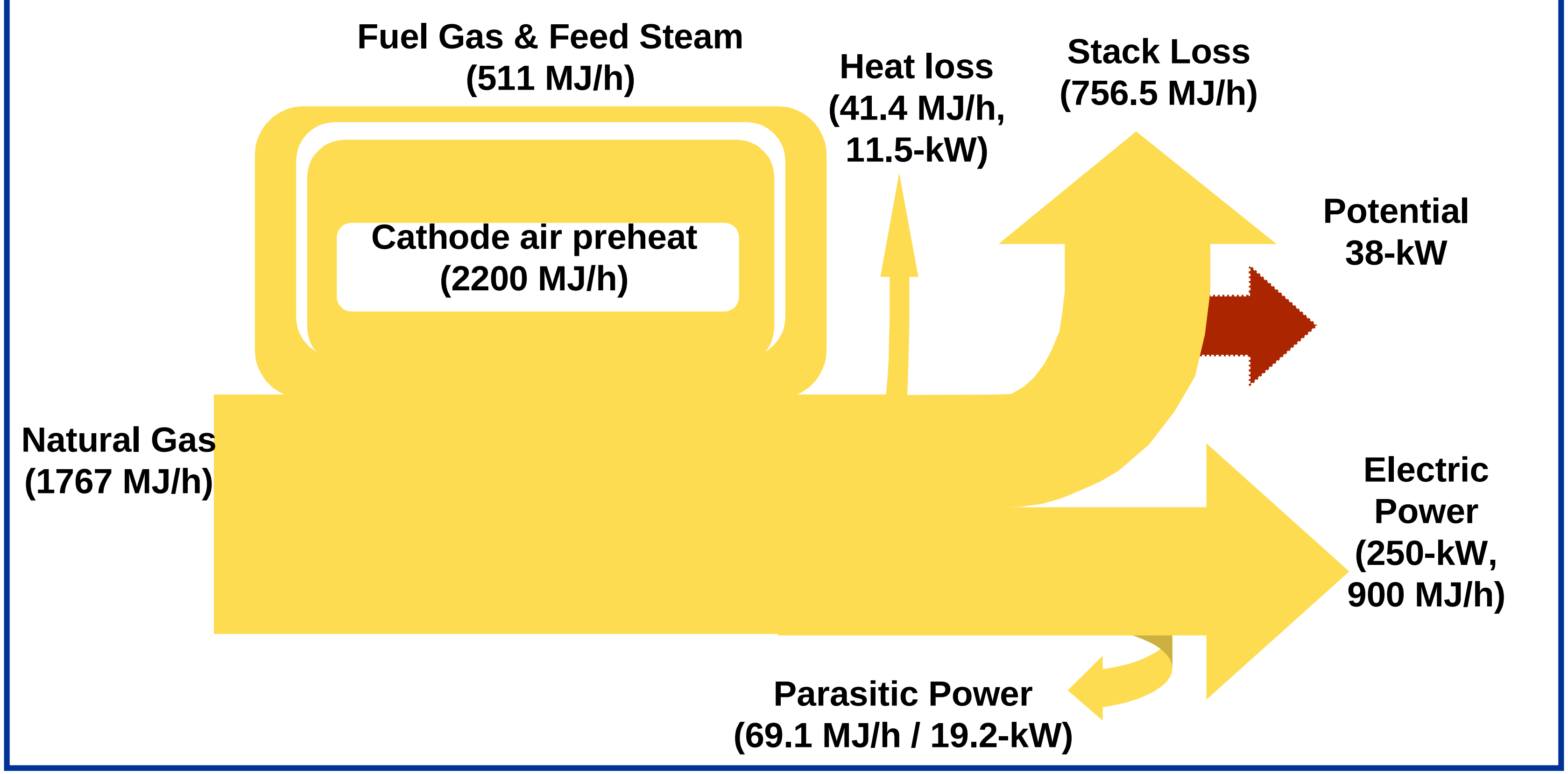


With careful thermal integration, a system efficiency of about 51% can be achieved in simple-cycle configuration.

Anode Fuel Utilization	85%
Fuel Cell, Cell Voltage	0.7 V
Fuel Cell Efficiency	47.1%
Reformer Efficiency	117%
Efficiency of Parasitics	75%
Cathode Inlet Air Temperature	650ºC
Cathode Excess Air (for Cooling)	7.7 times
Blower Pressure	1.17 bar
Exhaust temperature	293 ºC
Parasitic Loads	19.2 kW
Required Fuel Cell gross power rating	269.2 kW
Resultant Overall Efficiency	51.2%

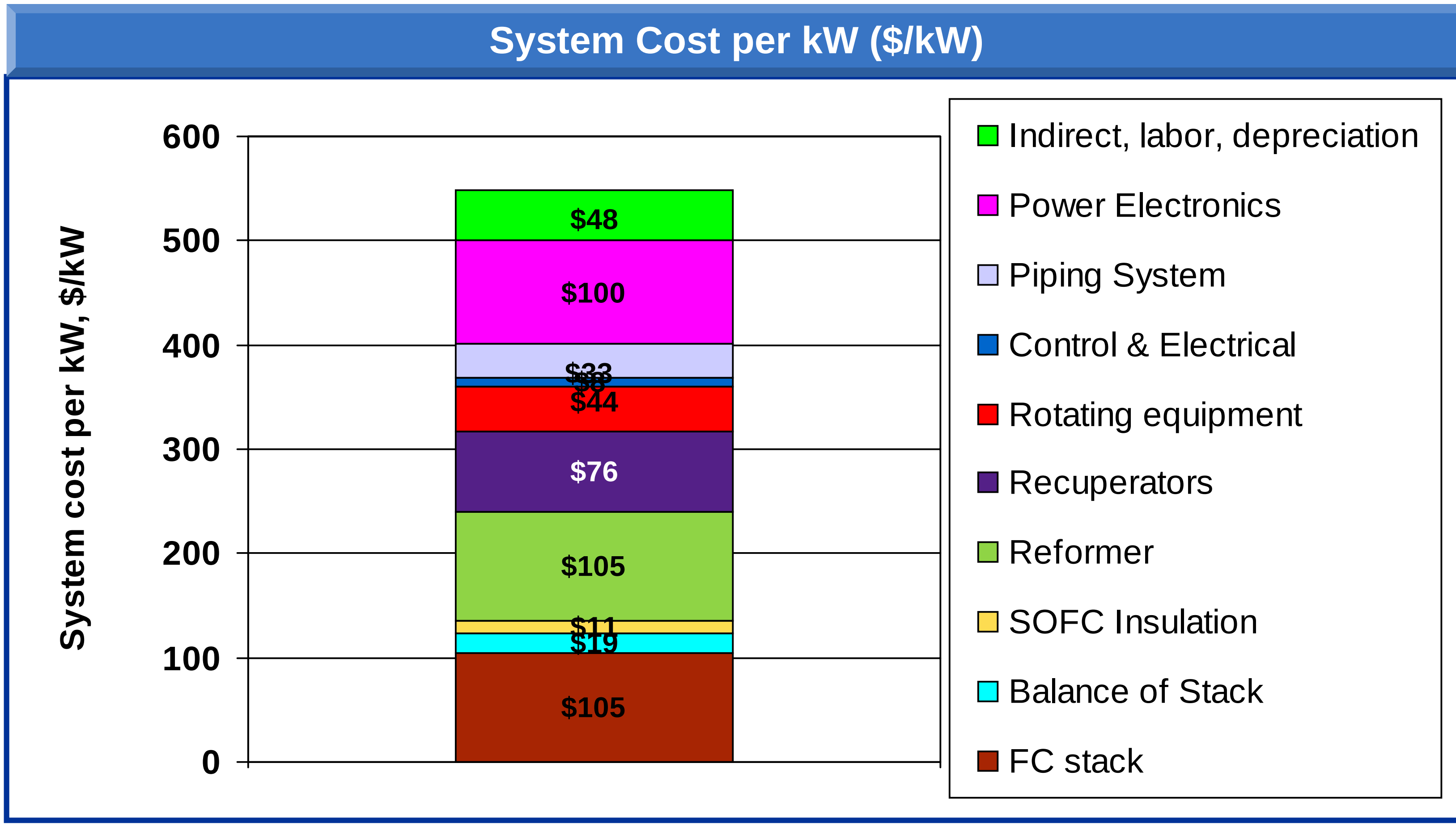
Extensive energy recovery from hot exhaust gas is critical to achieving high system efficiency.

Energy Flow in 250-kW net SOFC system (Based on LHV)



1. Heat loss term is heat loss out the exterior walls of system hot box enclosure and heat carried away by "active cooling" air
2. Potential for electric power from waste heat estimated with 90% recovery of enthalpy to make steam with 20% conversion efficiency to electric power.
3. Parasitics include natural gas compressor, water pump, cathode air blower and active cooling blower

The direct manufacturing cost of the 250 kW system is estimated to be around $150,000.



Installed cost ~ $1000 / kW

Integration of SECA modules into cost-effective high-performance larger-scale systems appears feasible.

- Integration of over fifty stacks appears feasible:
  - Several manageable configurations identified
  - Manifolding and interconnection losses acceptable
  - Cost savings in balance of plant
- High-efficiency, simple-cycle plant appears feasible; and results in attractive cost
  - Lower-efficiency, lower-cost systems may be more flexible in operation and preferable in some situations
  - Combined-cycle configurations may ultimately lead to even higher efficiency
- Cost and performance would be attractive
  - In the 250-kW system, benefits of economy of scale are largely offset by lower production volumes compared to 5-kW systems

Further improvements could be made, but additional challenges must be overcome.

- Achieving projected cost and performance requires:
  - Raising power density under realistic conditions (e.g. high fuel utilization)
  - Proving long life and high reliability of stacks (e.g. steady state and cycling)
  - Subsystem and component design and development
  - Achieving high manufacturing volumes (cost at intermediate production volumes may be critical to ultimate success)
- Ultimately, further system improvements could be made, mainly by improving stack performance:
  - Lower stack temperature operation
  - More internal reforming / direct oxidation
  - Increased stack temperature gradient
  - Larger stack tiles

Report Topics

1. Executive Summary
2. **Background, Scope & Approach**
3. System Design
4. Results
5. Conclusions & Recommendations
6. 20-MW Vision 21 Application

NETL would like to understand if and how SECA's SOFC stack technology could be used in larger power plants, such as NETL's Vision 21 plants.

- The Vision 21 power plant is a concept of a virtually pollution-free energy plant providing a variety of products: power, heat, fuels and chemicals
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SECA would like to understand the issues of scaling up 5-kW planar SOFC systems to higher capacity applications of 100-kW to 1-MW.

The objective for this study was to assess how individual SECA stack modules could be integrated into a 0.1 to 1-MW stationary power plant.

- The scale-up study addressed mainly the scale of key pieces of the balance of plant (using 5-kW SOFC stacks)
- For the fuel cell stack, key questions include:
  - What is the logical scale for the SOFC stack modules?*
  - How would stack modules be combined into super-modules and systems?
  - What are the implications for electric interconnection of the units?
  - What are the implications for manifolding of reactants and exhaust streams?
- For the balance of plant, key questions addressed included:
  - What scale or number of trains make sense for compressors, steam reformer,and heat recuperators
  - Is high pressure operation (above 1.5 bar) feasible?
  - What is the impact of scale-up on system performance and cost?
- How is availability impacted by design and layout of key components?
- Combined cycle operation could be used to increase the efficiency of the system but this is not part of the scope of work of this study

* To be addressed in parallel study TIAX is conducting for SECA.

We developed a conceptual design for a 250-kW_e distributed generation system based on SECA stack modules that meets agreed specifications.

Deliverables	◆ Thermodynamic design ◆ System layout ◆ Cost estimate		
Specifications	**System**	**Stack**	**Balance of Plant**
	◆ Total capacity 250-kW net ◆ Availability or on-line factor goal of 99% ◆ Electrical system efficiency goal of >50% (LHV) ◆ Annual production 2500-MW/yr (10,000 250-kW units per year) ◆ Surface temperature of package modules less than 45°C ◆ System voltage goal 350-380V 3-phase AC ◆ System life over 15 years	◆ 5 kW stack modules, based on anode-supported technology ◆ Cell voltage – 0.7 V ◆ Stack temperature 650 - 800°C (inlet - outlet) ◆ Power density 0.6W/cm^2 ◆ Maximum number of tiles per stack 100; ◆ 85% fuel utilization per pass in fuel cell	◆ Water use – supplied (no internal recovery of water included) ◆ Fuel used – natural gas ◆ Oxidant for reformer – steam ◆ Natural gas available at grid pressure of 20 inches water column gauge ◆ Combined cycle operation not included in scope

We used a five-task approach to determine a flowsheet and a likely layout to meet the agreed specifications.

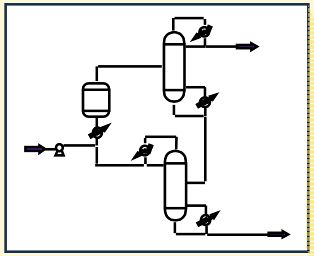
	Task 1	Task 2	Task 3	Task 4	Task 5
	Kickoff	**Flow sheet Analysis**	**Sub-system scale-up analysis**	**Performance and Cost Analysis**	**Conclusions**
Task Description	• Confirm scale-up targets • Review initial design options • Select one design option for detailed analysis	• Update Hysys models (include steam reforming and manifolding heat losses) • Determine configuration and component performance requirements	• Identify limits on balance of plant component sizes • Identify limits on manifolding stack units • Develop overall scale-up concept	• Optimize system to meet performance targets • Evaluate cost-effectiveness of scale-up concept	• Identify any gaps in knowledge or technology performance • Characterize implications for DOE • Identify issues related to combined cycle operation
Deliverables	• Scale-up targets • System configuration for detailed analysis	• Flow sheet configuration • Likely component performance requirements	• Maximum component sizes • One scale-up system concept	• Performance and cost for scale-up concept	• Gap analysis • List of RD&D opportunities for DOE • Combined cycle issue analysis • Presentation-style final report

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

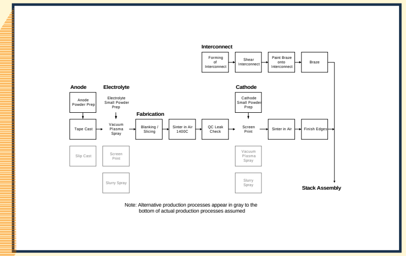
- Production volume: 2.5 GW/yr (2500 MW/yr)
  - 10,000 250-kW units per year (same production volume as 500,000 5 kW unit as in our SECA APU)
  - Stack production cost model based on previous Arthur D. Little, Inc. study with 250 MW/yr production (assuming same cost through modular production)
- SOFC stack assumptions were consistent with those used in our APU study:
  - 5-kW anode supported planar stacks
  - Stack operating temperature: 650 - 800°C (inlet - outlet)
  - Cell voltage: 0.7 V
  - Stack pitch of 5 cells/inch; Geometry: square cells; 64 tiles per stack
  - Total voltage 350-380V 3-phase AC goal
  - 85% fuel utilization at anode
  - Power density of 0.6 W/cm^2 (power density was increased to be consistent with the state of the art in cell design, e.g. Global Thermoelectric and MSRI data)
- Duty cycle load profile: assume constant load, steady state operation
- Availability factor goal: 99%
- Natural gas fuel available at pressure from gas grid (20 inches water column)
- Combined cycle operation implications were not part of the scope of this study

We used detailed thermodynamic system models, bottom-up cost estimates and quotes to design and cost the system components.

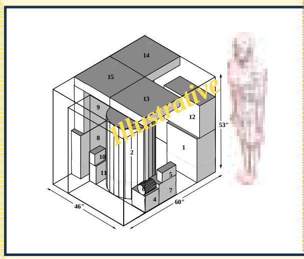
Methodology for Design & Cost Estimates



Thermodynamic System Model



Fuel Cell Manufacturing Cost Model



Conceptual Design and Configuration

Manufacturer Quotes For Heat Exchange

Component Prices For blowers, valves, sensors etc.

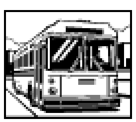
Equipment estimates for Reformer

Factory Expense

Direct labor

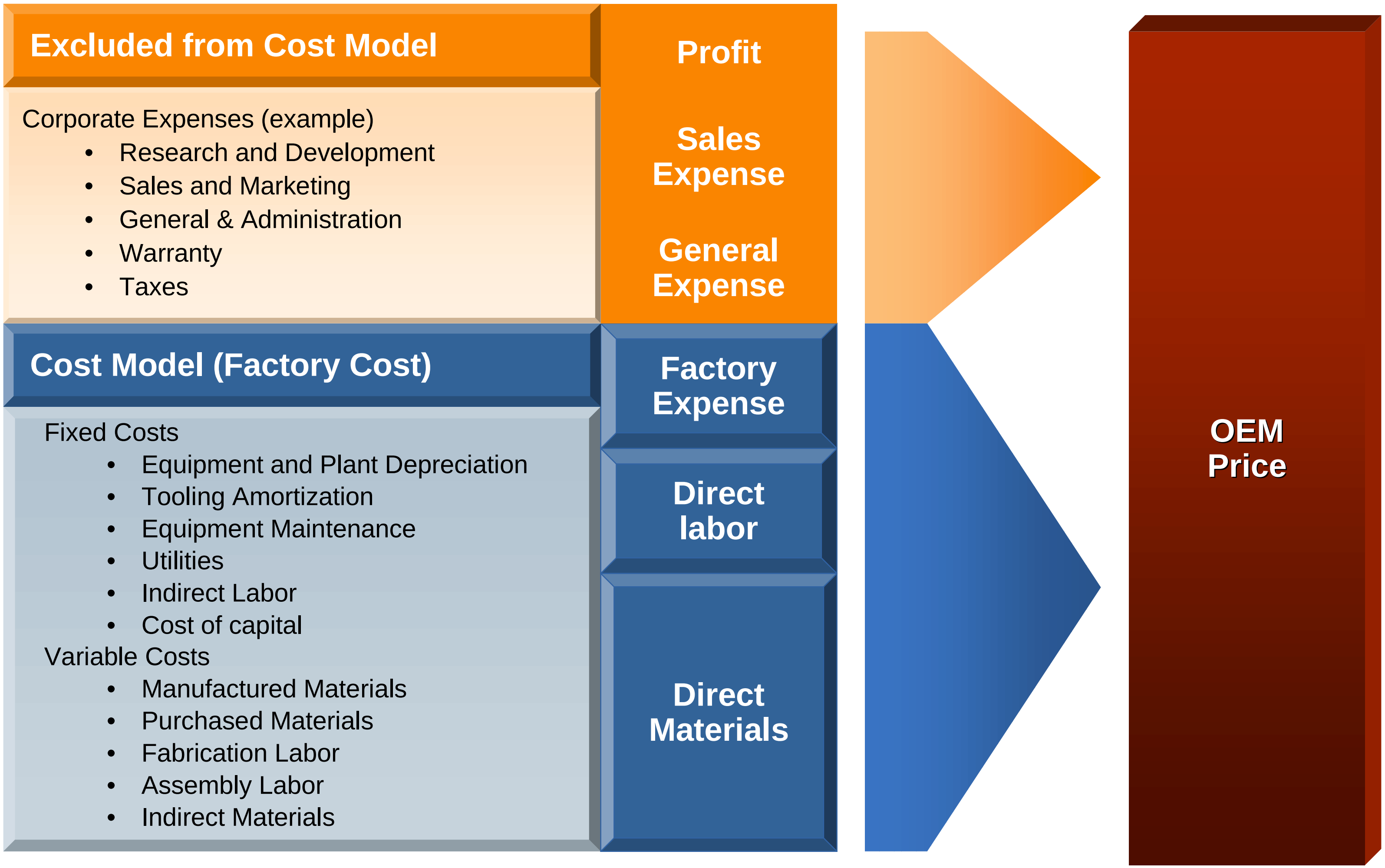
Direct Materials

Not in scope of Project



Market Model

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



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

The cost model contains both purchased components and manufactured components.

- Built on existing TIAX cost models for SOFC stack manufacture and BoP
- Cost elements for the fuel cell stack are outlined in table on this page
- 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
◆ Air blower for cathode air ◆ Natural gas compressor ◆ Air blower (for active cooling) ◆ Water pump ◆ Air and fuel filters ◆ Control and solenoid valves ◆ Controllers for rotating equipment ◆ Control logic, processors and hardware ◆ Piping, fittings & connectors ◆ Thermocouples/sensors ◆ Wiring for sensors & valving ◆ Insulation (high and low temperature)	◆ Fuel cell stack ➤ Anode ➤ Cathode ➤ Electrolyte ➤ Interconnects ➤ Stack assembly ◆ Fuel cell stack hardware ◆ Fuel cell packaging ◆ Recuperators ◆ Zinc bed ◆ Steam reformer
Raw materials (examples) ◆ Steel sheet ◆ Metal foil ◆ Chemicals ◆ Nickel oxides	

Report Topics

1 Executive Summary

2 Background, Scope & Approach

3 System Design

- A System Modeling
- B Component Design

5

6 20-MW Vision 21 Application

The system design section is organized into two parts.

- An overview of the system modeling will be presented for the base case
- The design of the key components for the base case is presented at a high level
- The system layout and cost analysis are presented in Section four
- Two alternative system layouts are described in Appendix B:
  - Split Cathode air preheater
  - Cathode air recycle using a jet-pump

The following key assumptions were used to model the 250-kW (net) system. The 5.0-kW fuel cell stacks are cooled with excess cathode air.

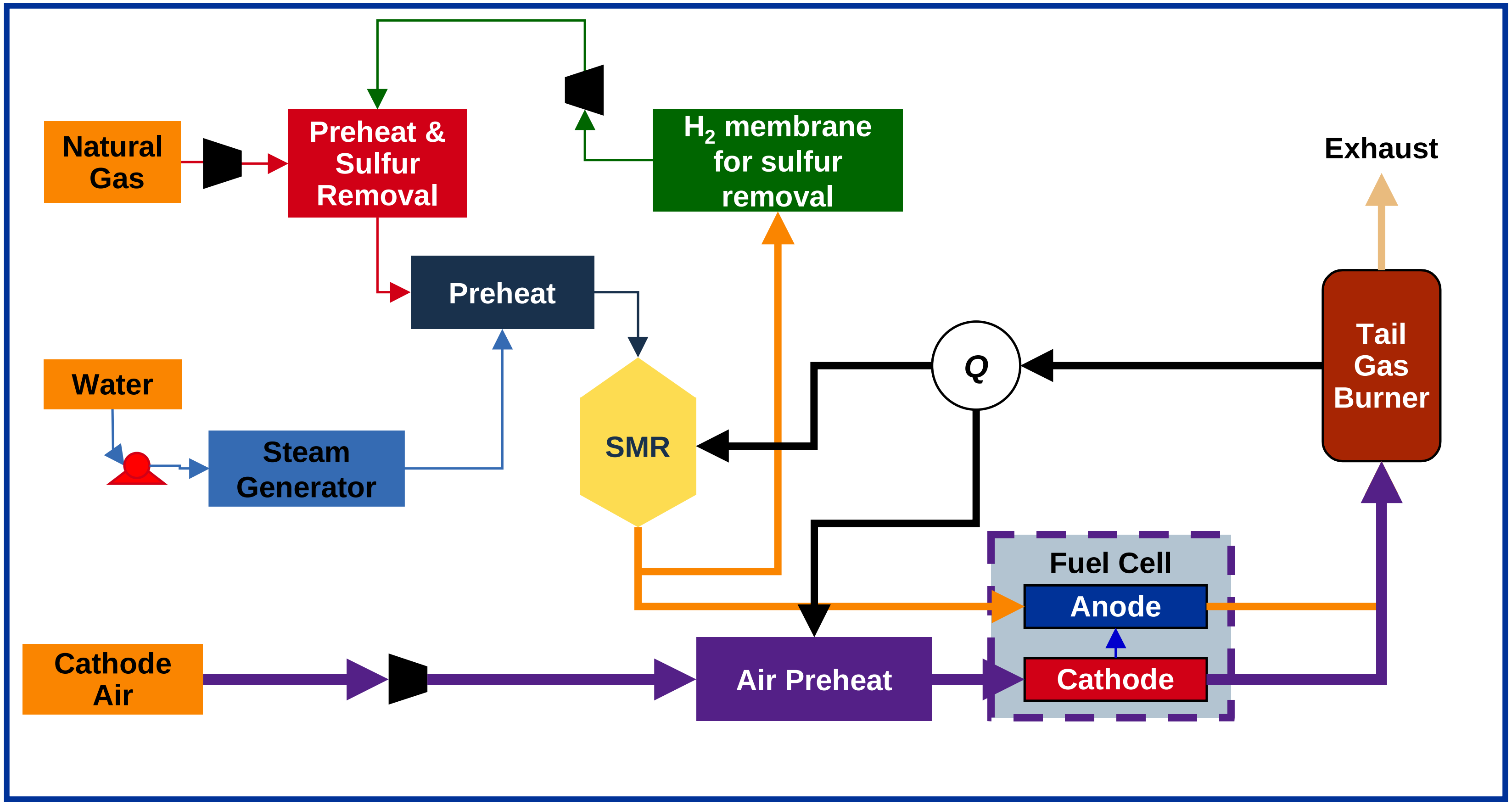
	This Study	5-kW net POX / SOFC APU[1]
Fuel	Natural Gas	Gasoline
Reformer	SMR	POX
Cathode air inlet temperature	650ºC	650ºC
Anode fuel utilization	85%	90%
Power density, W/cm²	0.6	0.3
Single cell voltage	0.7 V	0.7 V
Fuel cell operating temperature	800ºC	800ºC
Power per stack	5-kW gross	5.5-kW gross
Number of stacks per system	54	1
System rating, net	250-kW	5-kW

Changes from the SECA APU study[1] were made because:

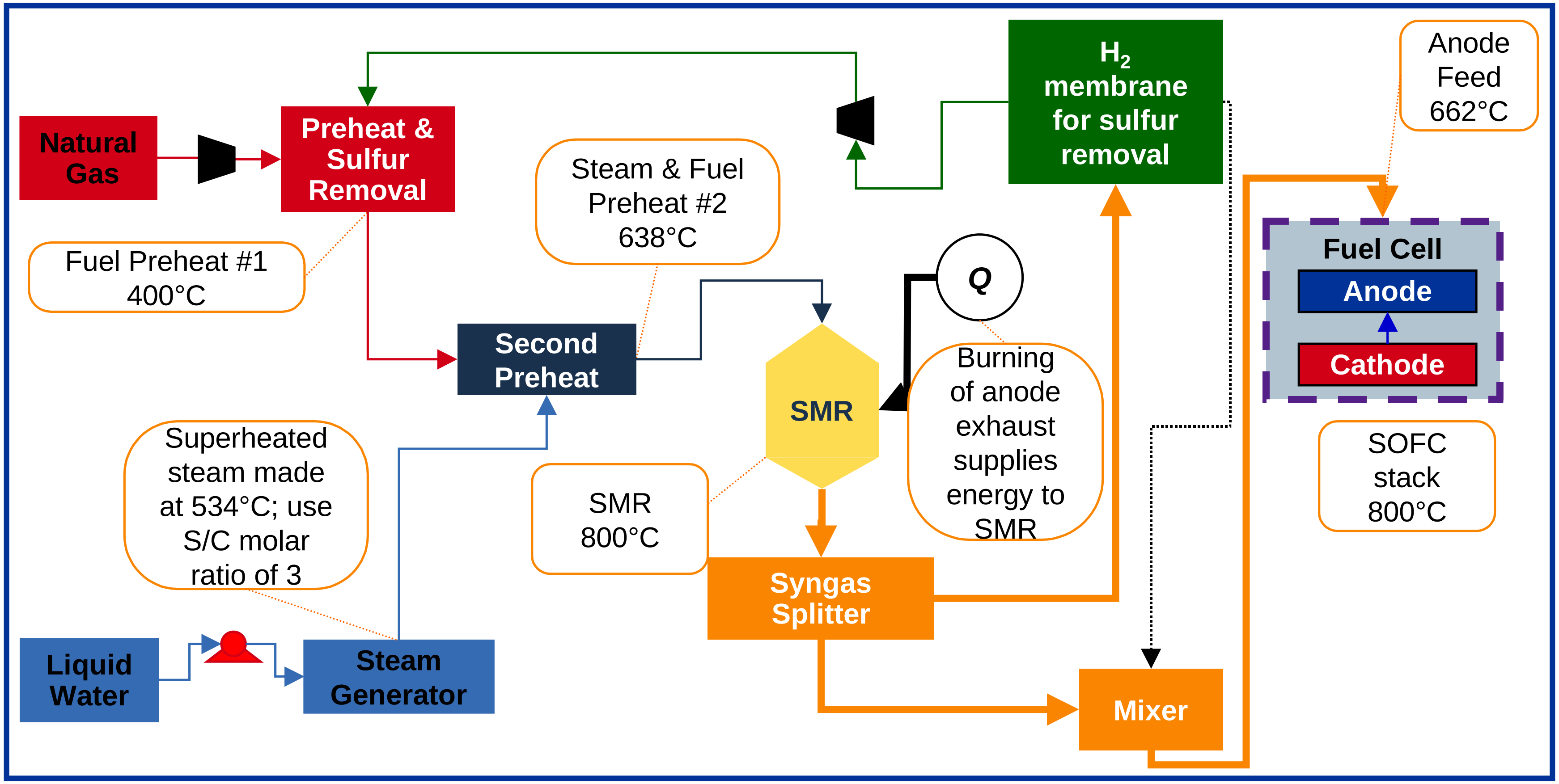
- Natural gas fuel is more consistent with a distributed generation (DG) application
- Steam reformer is consistent with higher efficiency continuous operation of DG application
- Modified fuel utilization and power density are consistent with state-of-the-art, as determined by Arthur D. Little in recent EPRIsolutions study

1. "Conceptual Design of POX/SOFC 5-kW net System", Report for USDOE NETL, Jan. 8, 2001

A tightly integrated steam reformer and air recuperator were used to achieve the desirable system efficiency.

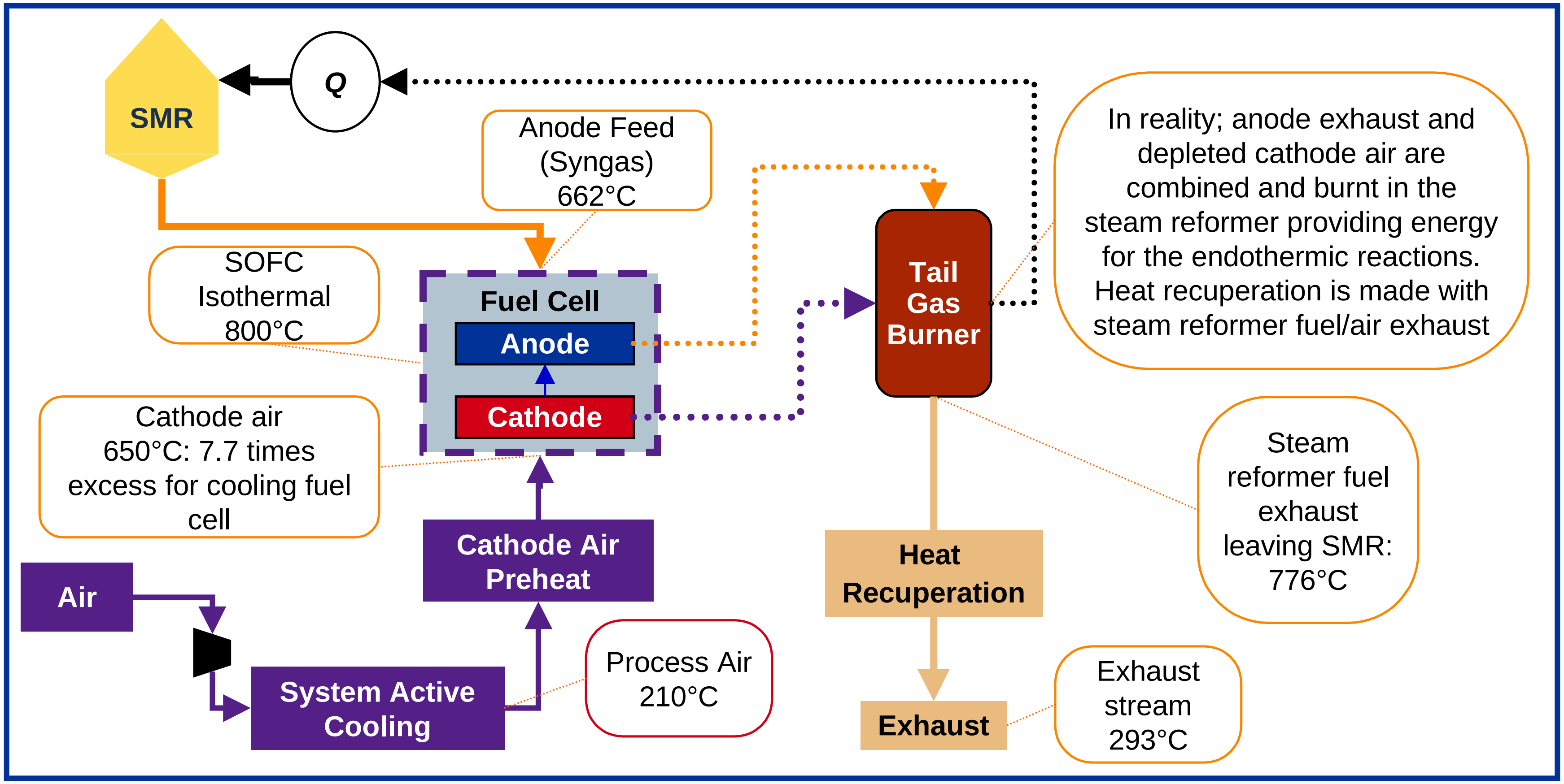


In a steam reformer the natural gas is partially converted using unused anode exhaust gas as fuel to drive the endothermic reforming reactions.



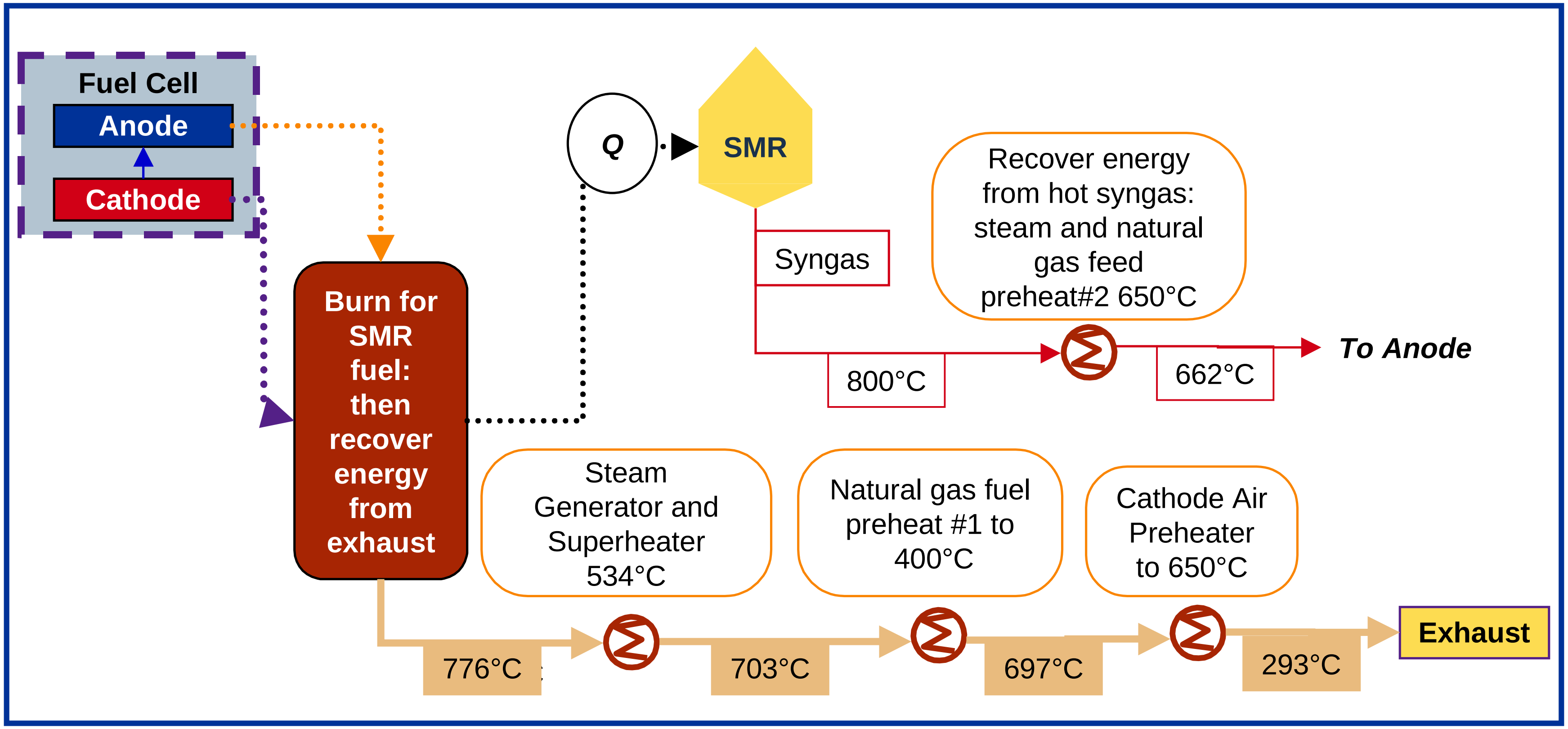
Note: Airflows not shown.

The base case is a "one-pass" operation of the cathode cooling air which has to be preheated to 650°C prior to introduction into the cathode.



The process cathode air is first preheated in the active cooling system used to reduce insulation requirements for the system.

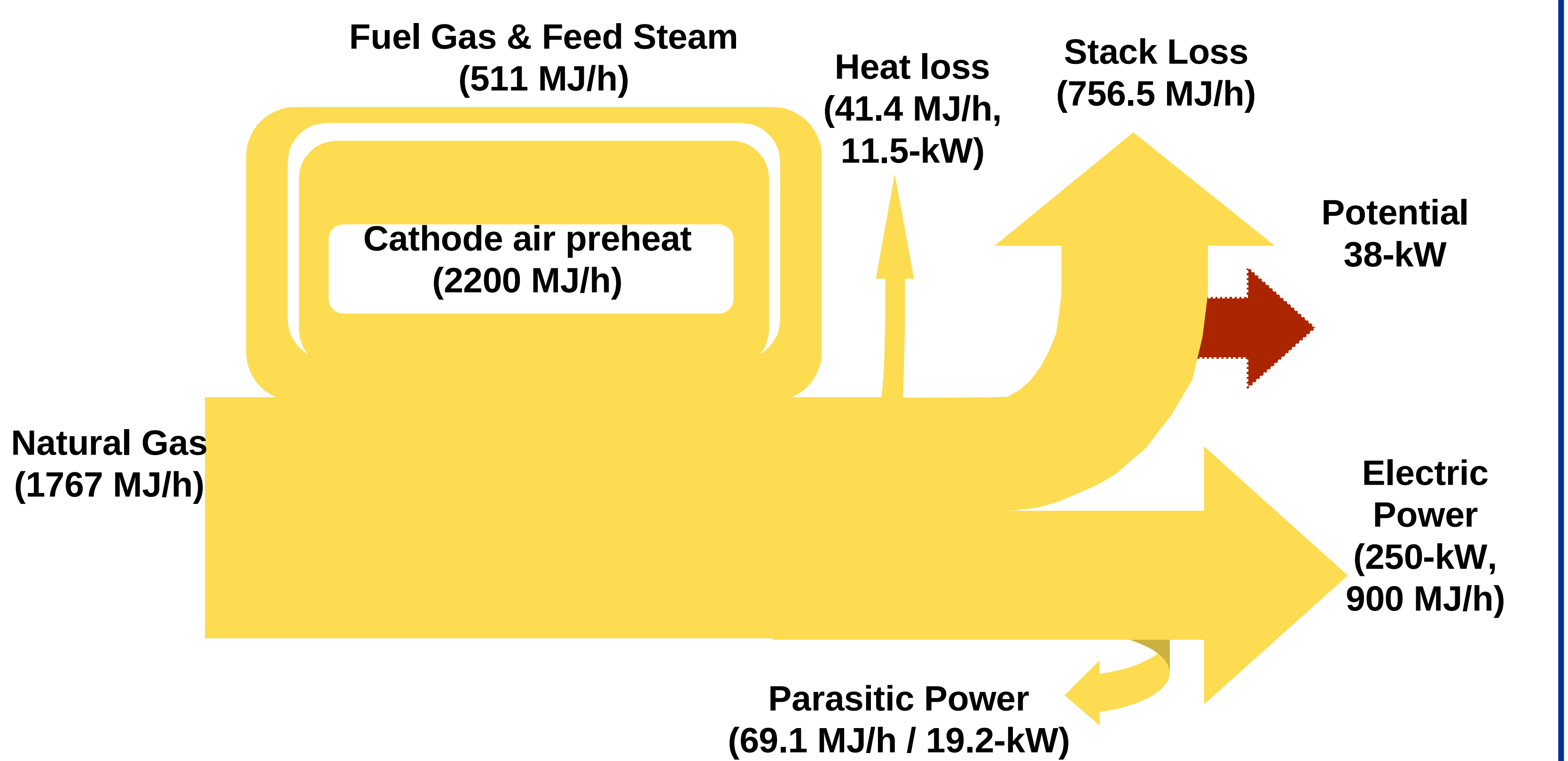
The system integration includes a steam generator/superheater (feeding the SMR), cathode air preheat capability, and natural gas preheat.



Heat exchanger layout was chosen to minimize overall heat exchange surface area requirements.

Recovery of energy from hot exhaust gas is critical to maintaining high efficiency power generation.

Energy Flow in 250-kW net SOFC system (Based on LHV)



1. Heat loss term is heat loss out the exterior walls of system hot box enclosure and heat carried away by “active cooling” air
2. Potential for electric power from waste heat estimated with 90% recovery of enthalpy to make steam with 20% conversion efficiency to electric power.
3. Parasitics include natural gas compressor, water pump, cathode air blower and active cooling blower

Report Topics

The 250-kW (net) system uses pre-reforming of natural gas (SMR), air movement system (blowers), and heat exchange for energy recovery.

Gas Pre-reforming	Fuel Cells & Balance of Stack	Recuperators	Rotating Equipment	Balance of Plant
◆ Sulfur removal system (ZnO sorbent) for pipeline natural gas ◆ Hydrogen membrane for hydrogenating mercaptan sulfur species ◆ Tubular steam methane reformer using fuel cell anode exhaust as fuel (water-gas shift beds and CO-clean-up not required)	◆ Fuel cell stacks (consisting of unit cells) [1] ◆ Balance of stack[2] ◆ Fuel cell modules plant packaging and insulation ◆ Manifolding for stacks ◆ Power conditioner	◆ Cathode air preheater ◆ Natural gas preheater ◆ Steam & natural gas secondary preheater ◆ Steam generator & superheater	◆ Main cathode air blower ◆ Recycle cathode blower (if needed) ◆ Water pump ◆ Natural gas compressor (if insufficient pressure available from gas grid) ◆ Hydrogen recycle compressor ◆ Active cooling air blower	◆ Control & electrical system ➢ System sensors ➢ Controls ➢ System logic ➢ Safety contactor ◆ System piping ◆ System insulation ◆ Water conditioning for steam generation

1. The fuel cell stack includes cathode, anode, electrolyte, interconnects, and layer assembly and stack assembly
2. The balance of stack includes endplates, current collector, electrical insulator, outer wrap and tie bolts. It is assumed that the stack is internally manifolded.

Power generation by steam was not considered in this study.

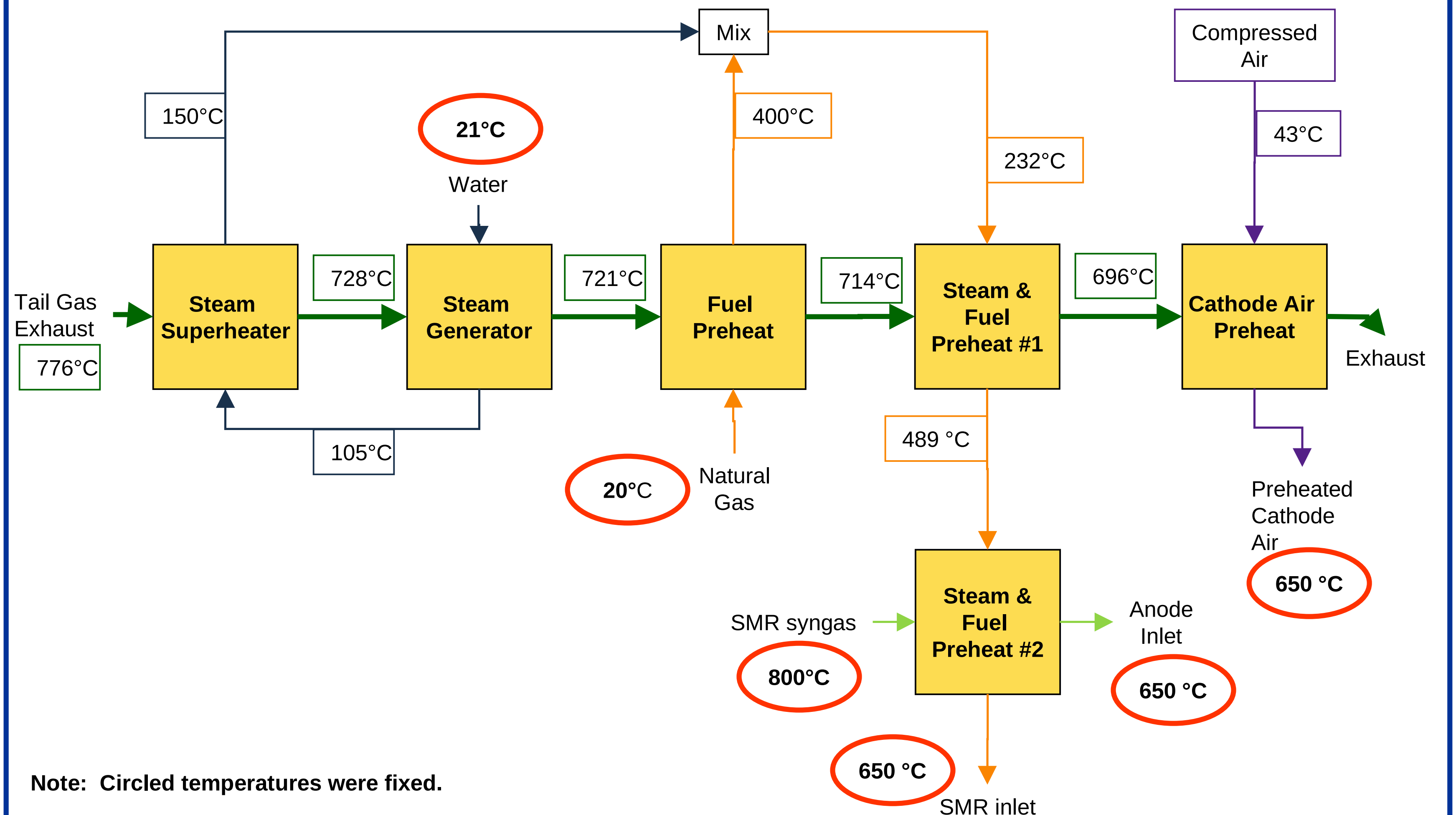
The goal of this analysis was to define the tradeoffs associated with sizing the heat transfer and air handling equipment for a 250-kW SOFC system.

- The components can be modularized to achieve performance targets while optimizing:
  - Size
  - Weight
  - Cost
  - Overall system availability
- Larger capacity equipment takes advantage of economy of scale (volumetric capacity) and efficiency benefits
- Smaller capacity equipment (and more trains) could take advantage of cost benefits of higher production volume
- We initially focused on the heat exchangers, as they are likely the most critical and costly elements of this subsystem

We used a combination of manufacturers' inputs and analytical modeling to conduct the study.

- The baseline analysis assumed a single flow train (e.g. single train operation)
- Data for this configuration was obtained from various heat exchanger manufacturers
- We examined several types of heat exchanger construction to determine the cost and size implications of each
  - Shell and tube
  - Compact finned (plate and fin)
- We then used heat transfer and costing models to develop tradeoff curves for modularizing the components i.e., splitting the flow stream into parallel paths
  - Multiple smaller units could potentially reduce costs by increasing production volume
  - Multiple units can also increase system reliability by lessening the impact of maintenance or repair

Six heat exchangers were identified in the flow train.



Note: Circled temperatures were fixed.

Commercial heat exchange manufacturers provided estimates for a prototype system.

- We approached five heat exchanger manufacturers to provide cost and sizing estimates
  - The companies were selected to represent a range of capabilities and industries that they serve
- The companies were provided with system flow requirements and asked to produce the optimally sized system
  - Flow rates, temperatures, and compositions were specified based on the thermodynamic modeling results
  - Temperature balances could be adjusted slightly if necessary
  - Pressure drops were not specified in order to allow the most design latitude, although it is obviously desirable to minimize them

Of the five manufacturers contacted, only two were willing to quote this system.

Company	Heat Exchanger Type	Result
Bos-Hatten, Inc.	Shell and tube	Quote received
Stewart Warner South Wind Corp.	Plate and fin	Quote received
Industrial Heat Transfer	Plate and fin	No quote: Could not produce the large cathode air preheater
API Heat Transfer, Inc.	Shell and tube	No quote: Process temperatures were too high
Thermally Engineered Manufactured Products	Plate and fin	No quote: The company could not handle a project of this magnitude

A number of concerns were raised by the manufacturers, even among those who provided quotes.

- Size of the cathode air preheater
- High fluid temperatures
  - High temperature stainless steels must be used for every heat exchanger
  - Material costs will be high
- Large temperature differential in both the fuel and cathode air preheater
- Questioned cost benefit of multiple flow paths:
  - More material would be required for packaging
  - More labor required for fabrication
  - More room for inefficiencies
- Cleanability

We received quotes from Bos-Hatten for a single prototype shell and tube system.

- In general, this heat exchanger construction results in relatively large and costly equipment
- Most of the cost is associated with the endplates
  - It is desirable to keep the diameter of the heat exchangers as small as practically possible, which results in long components (high aspect ratio L/D)
  - It is relatively expensive to construct multiple parallel flow trains

Superheated Steam Generator	Length (ft)	5.10
	Diameter (ft)	0.38
	Cost ($)	8,281
Steam Generator	Length (ft)	8.90
	Diameter (ft)	2.00
	Cost ($)	17,222
Fuel Preheat	Length (ft)	6.70
	Diameter (ft)	0.55
	Cost ($)	10,815
Fuel and Steam Preheat One	Length (ft)	7.00
	Diameter (ft)	0.72
	Cost ($)	12,927
Fuel and Steam Preheat Two	Length (ft)	8.70
	Diameter (ft)	0.72
	Cost ($)	18,934
Cathode Air Preheat	Length (ft)	23.10
	Diameter (ft)	2.17
	Cost ($)	144,948

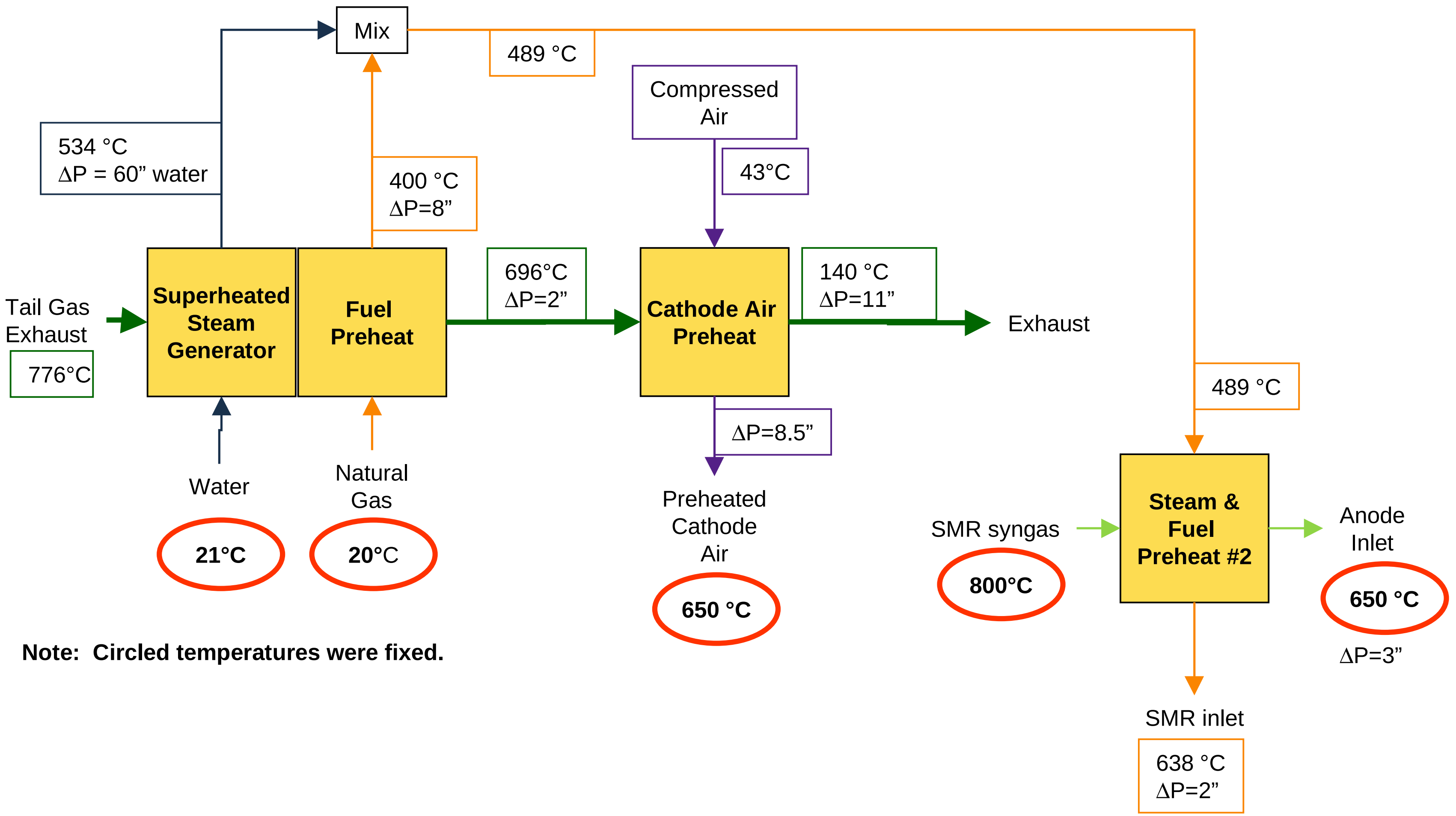
NOTES:
1. Shell and tube designs; 1 unit per year production
Source Bos-Hatten

The component size and weights are fairly reasonable, with the exception of the cathode air preheater.

We then focused on plate and fin heat exchangers for their compact footprint and potentially lower cost.

- A manufacturer proposed a system redesign to minimize the number of required preheaters
  - Combined the steam generator and superheater
  - Combined the two fuel/air preheaters
  - Suggested packaging the steam generator and fuel preheater together to minimize inlet and outlet connections and packaging requirements

The proposed system redesign resulted in four heat exchangers.



Note: Circled temperatures were fixed.

Source: Stewart Warner South Wind

The plate and fin heat exchangers are substantially more compact and light-weight compared to their shell and tube counterparts.

Superheated Steam Generator	Dimensions (in)	18.65 x 14.06 x 1.5
	Weight (lbs)	25.4
Fuel Preheat	Dimensions (in)	5.35 x 5.62 x 1.5
	Weight (lbs)	Included in Steam Generator
Fuel and Steam Preheat One	Dimensions (in)	6.0 x 6.2 x 6.0
	Weight (lbs)	11
Cathode Air Preheat	Dimensions (in)	40.53 x 55 x 50
	Weight (lbs)	6,178

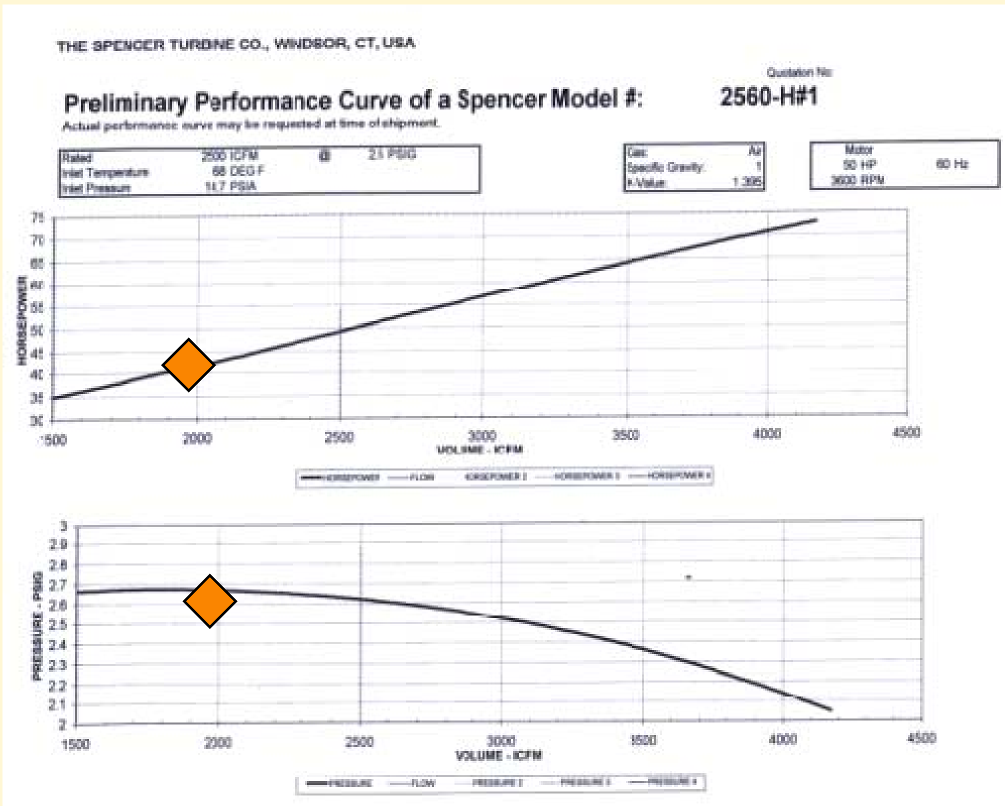
Source: Stewart Warner South Wind

A single heat exchanger train is likely to be the lowest-cost configuration.

- Multiple, parallel heat exchangers of smaller capacity were compared on a cost basis to the single flowtrain
- We tested several assumptions regarding the benefits of multiplicity:
  - Manufacturing costs can be reduced by increasing annual production volumes
  - Reliability can be increased by added redundancy in the system
  - System availability can be optimized with multiple trains that can be serviced at different times
- Any potential cost benefit of higher production volumes is offset by the increased labor and material requirements for the smaller units
  - Labor costs are dominated by the number of welds required at the edges of the splitter plates for this fin/plate design
  - Multiple smaller units increase the total number of welds compared to a single unit handling comparable flow (which will increase labor costs)
  - Each smaller unit will require separate heads and collectors as well as manifolds, adding to material costs
  - Once production volumes exceed 1000 units/year, total heat exchanger costs are basically constant, thereby eliminating any volume advantage at the target production rate of 10,000 power generation units per year
- Since heat exchangers are near 100% reliable, adding redundancy will not enhance overall system reliability
- Typically no service or maintenance is required for these heat exchangers, so there is no increase in system availability with multiple flowtrains

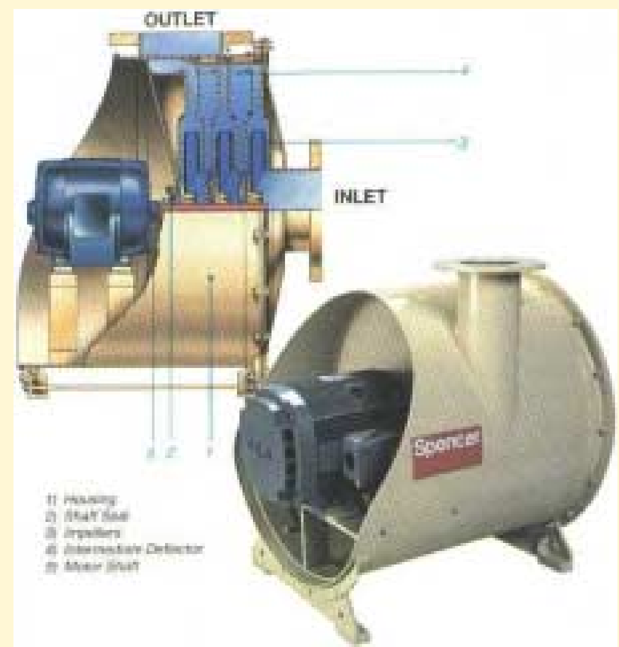
The cathode air pressure and air flow rate can be provided by a single multistage centrifugal blower.

50 hp blower requires 230/460 V, 3 phase, 60 Hz
Dimensions H: 48.75”, W: 45”, D: 51.56”

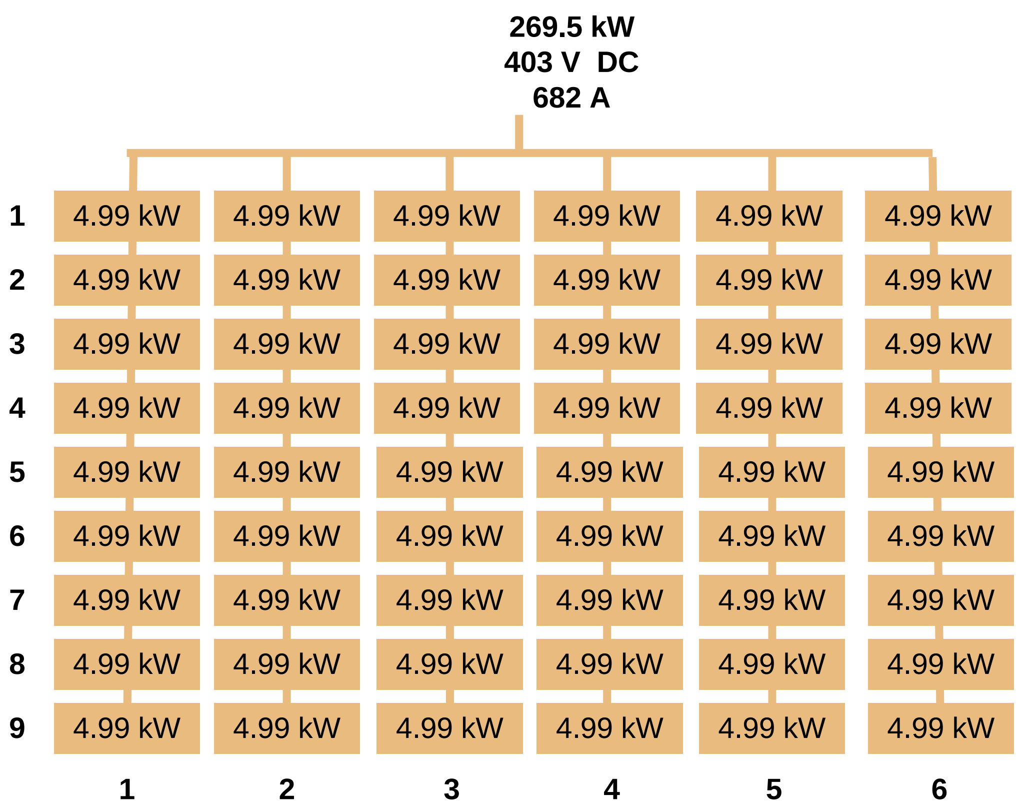


Volume Costing		
1-10	10-100	100-1000
$ 10,933	$ 9,001	$ 8,666

*Quote received from Environmental Air Systems



The fuel cell system layout comprises six parallel strings containing nine 4.99-kW units in series each.



Required fuel cell gross power rating	**269.2 kW**
Gross power rating without electrical resistance losses	**269.5 kW**
Total number of 5.09-kW units	**54**
System AC voltage	**383 V**
Assumed power electronics efficiency	**95%**
System DC voltage	**403 V**
Number of cells per stack	**64**
Stack voltage	**44.8 V**
System current	**682 A**
Parallel string current	**114 A**

We evaluated possible arrangements for the system thermal insulation and internal electrical connections based on a number of characteristics.

System Characteristics	Significance
Simplicity of a single 5-kW unit replacement in case of a failure: • Electrically disconnecting a single failed unit and reconnecting the system • Physical removal of a single failed unit from the system	• It is desirable that electrical connections could be broken and established without physical rewiring of the system at high temperature, for example, from an electrical control station • Physical removal of a failed unit without interference with the operating system at high temperature is the most advantageous
Low electrical power loss due to connector's resistance	• Minimal length of electrical connectors is advantageous • Connectors at lower temperature are preferred due to a decrease in electrical resistivity at low temperature for the materials considered for the application
Simplicity and convenience of system control and monitoring	Both temperature monitoring and voltage monitoring in the system are necessary to detect a failure
Cost	Capital and maintanance cost

A high temperature cable suitable for this application was identified.

Manufacturer	**Cable USA, Inc.**	
Material	**Copper, 27% nickel clad**	Cable USA
Cable size	**1 awg**	Cable USA
Electrical resistivity	**2.24×10^{-6} Ω /cm**	At 20°C; SouthWire Company
Temperature coefficient of resistance	**0.0068**	For pure copper
Price	**$5,995 per 1,000 ft**	Assuming annual production of 150,000-250,000 ft; Cable USA

Internal electrical connections do not introduce high power loss due to electrical resistance.

System Parameters	
Total internal electrical connections length	**40 feet**
Assumed average operating temperature	**750°C**
Total electrical connections resistance at 750°C	**0.0254 Ω**
Total power loss due to electrical resistance in the internal connectors	**0.32 kW**

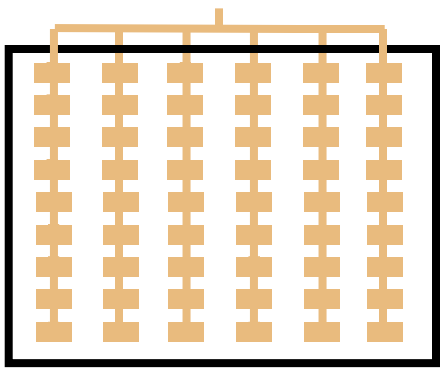
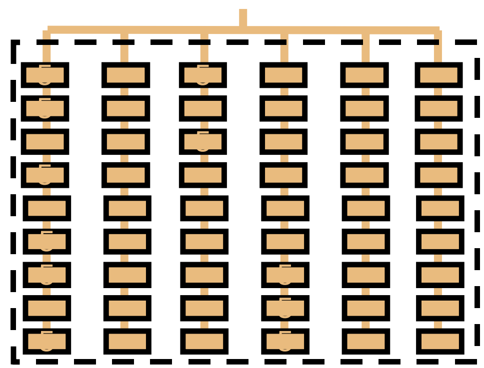
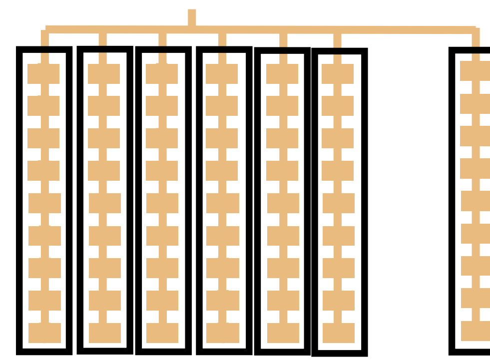
Total capital cost of internal cables	**$230**

Capital cost of the electrical connections is insignificant even for such relatively expensive high temperature cables as in this application.

Since fuel cells are modular, we were faced with design choices in the level of system modularity.

- Planar SOFC stacks were assumed to produce 4.985-kW each, at 45 V (this is similar to tubular SOFC sub-modules of 3x8 tubes, referring to power)
- 54 stacks will be needed to make a 250-$kW_{e,net}$ DG system
- Different levels of modularity can be designed into the system:
  – Completely modular = 54 x 4.99-kW standalone units
  – Completely integrated = 54 stacks in one integrated SOFC system
- Several considerations must be made in making the modular design choices:
  – More integration could provide benefits:
    - Economy of scale of capacity
    - Reduced heat losses
    - More opportunity to build up voltage, more compatible with DG power electronics
  – More modular designs would provide:
    - Independent operation leads to higher system availability (unlikely all 54 units fail at same time)
    - Economy of scale of numbers produced
    - Simpler manifolding (only fuel required)

We considered three possible arrangements for the system thermal insulation and internal electrical connections.

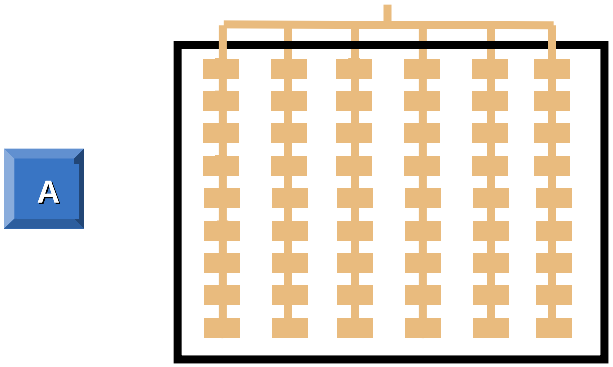
A	B	C
		
◆ All 4.99-kW SOFC units are placed in one thermally insulated box ◆ Electrical connections are inside the box, at high temperature	◆ Each 4.99-kW unit is placed in a separate box. Thermal insulation covers the common surface facing ambient atmosphere with an option of reaching for any unit ◆ Electrical connectors are brought outside the boxes and to an electrical control station	◆ Each parallel string of 4.99-kW units is placed in a separate thermally insulated box ◆ An additional backup string of nine 4.99-kW units could be added ◆ Electrical connections are inside the boxes, at high temperature

We chose for configuration A as the base case, expecting it to have the lowest manufactured cost.

System Parameters	System Configuration		
	A	B	C
On-the-fly failed unit replacement	–	+++	+++
Exposure of stack compression hardware to heat	–	++	-
Power Loss due to Electrical Resistance	+++	–	+++
System Control and Monitoring	+	+++	++
Cost	++	–	–

Key: Rating **+++** = Good Performance, **–** = Poor Performance

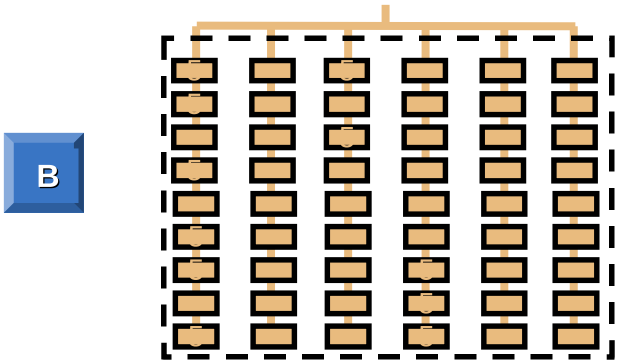
Packing all 4.99-kW units in one hot box has low power loss due to electrical resistance but has a challenging unit replacement procedure.



System Parameter	Rating	System Characteristics
Failed unit replacement	–	In order to remove a failed unit, an operating system hot box at 600-800°C would have to be open to perform unit replacement and rewiring
Power loss due to electrical resistance	+++	Units can be placed at a minimal possible distance from each other, thus allowing minimal connector length
System control & monitoring	+	Temperature monitoring of a single unit will be complicated due to other units being in close proximity to it in several directions. Voltage monitoring is hard to perform at a temperature close to 800°C. A total voltage output of a single string of units is available for monitoring but with lower failure detection level.
Cost	++	Minimal capital cost and very high maintanance cost due to the complexity of a failed unit procedure

Key: Rating **+++** = Good Performance, **–** = Poor Performance

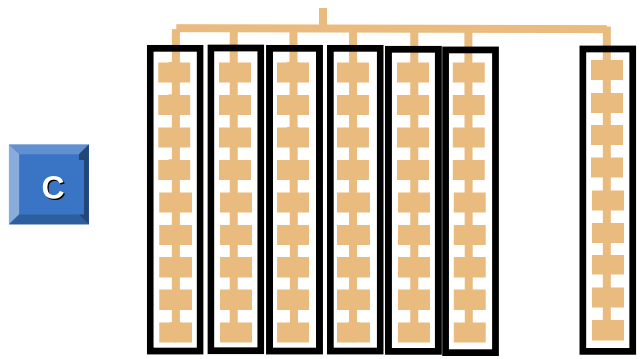
Packing every unit in a separate hot box connected to an electrical control station is likely to have high cost and high power loss.



System Parameter	Rating	System Characteristics
Failed unit replacement	+++	A failed unit can be replaced with minimal disturbance of an operating high temperature system. Electrical connections are operated remotely from the electrical control station with no interferance with the operating system
Power loss due to electrical resistance	–	Relatively long cables are needed to create the connections between each 5-kW unit and the electrical control station
System control & monitoring	+++	Temperature monitoring of a single unit is more precise than in other cases due to relative insulation of a single unit from others. Voltage output monitoring for every cell can be easily performed at the electrical control station without the complications of measurements at high temperature.
Cost	–	High capital cost and a prohibitive operating cost of long electrical connections with intensive cooling requirements. Cooling is necessary in order to decrease the cable temperature to a temperature close to ambient in order to operate the control station. (Cable is also not likely to perform well under such large temperature gradients).

Key: Rating **+++** = Good Performance, **–** = Poor Performance

Packing each parallel string in a separate insulated hot box has high capital cost while other characteristics are favorable.

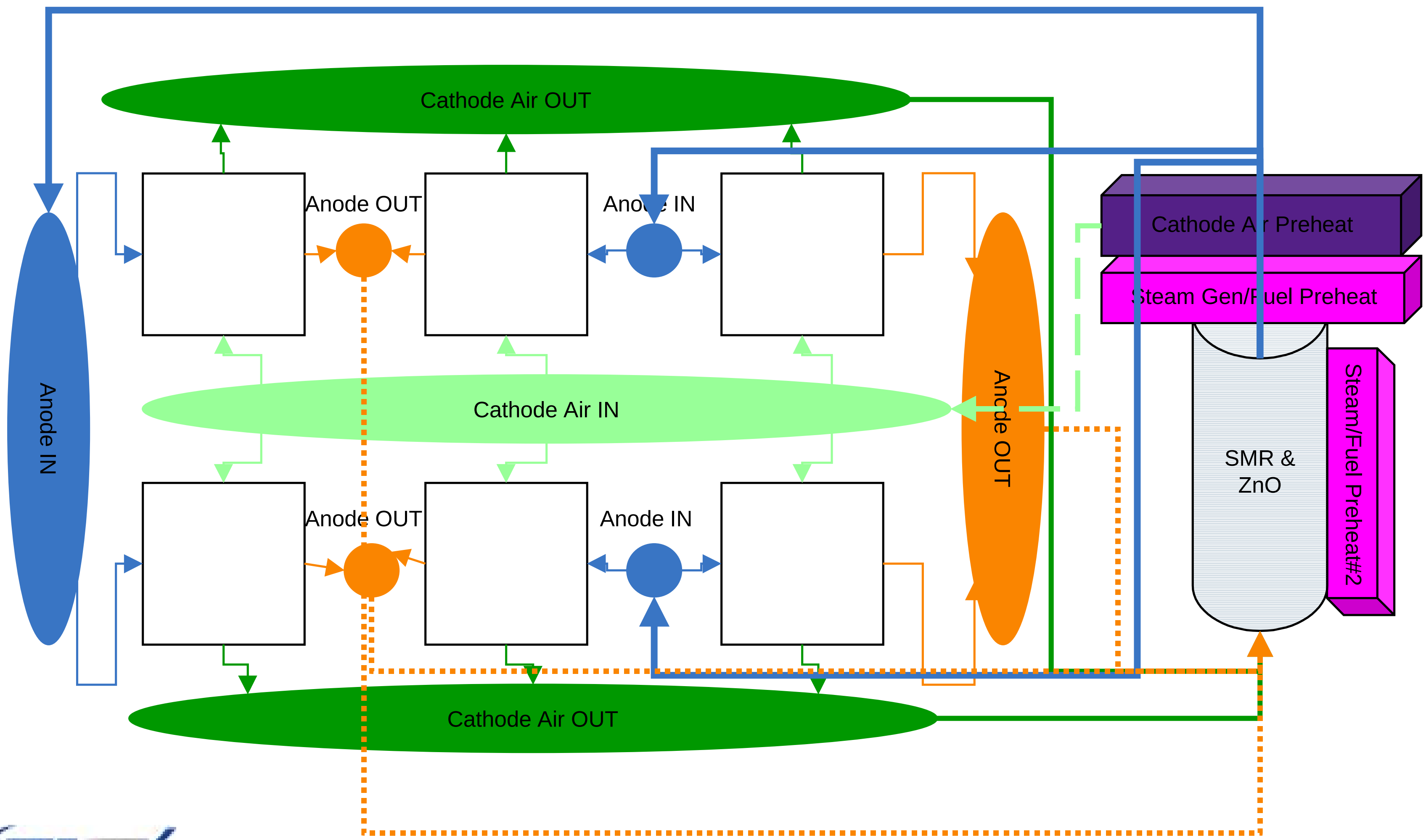


System Parameter	Rating	System Characteristics
Failed unit replacement	**+++**	In order to remove a failed unit, a string with the failed unit will be disconnected and cooled down before unit replacement. An additional full string will be brought on-line in this case
Power loss due to electrical resistance	**+++**	Units can be placed at a minimal possible distance from each other, thus allowing minimal connector length
System control & monitoring	**++**	Temperature monitoring of a single unit will be more accurate than in the case of a common hot box due to less interference from other units. A total voltage output of a single string of units is available for monitoring but with lower failure detection level than in case of a single unit monitoring.
Cost	**–**	High capital cost due to the additional string requirement. Lower operating and maintanance cost.

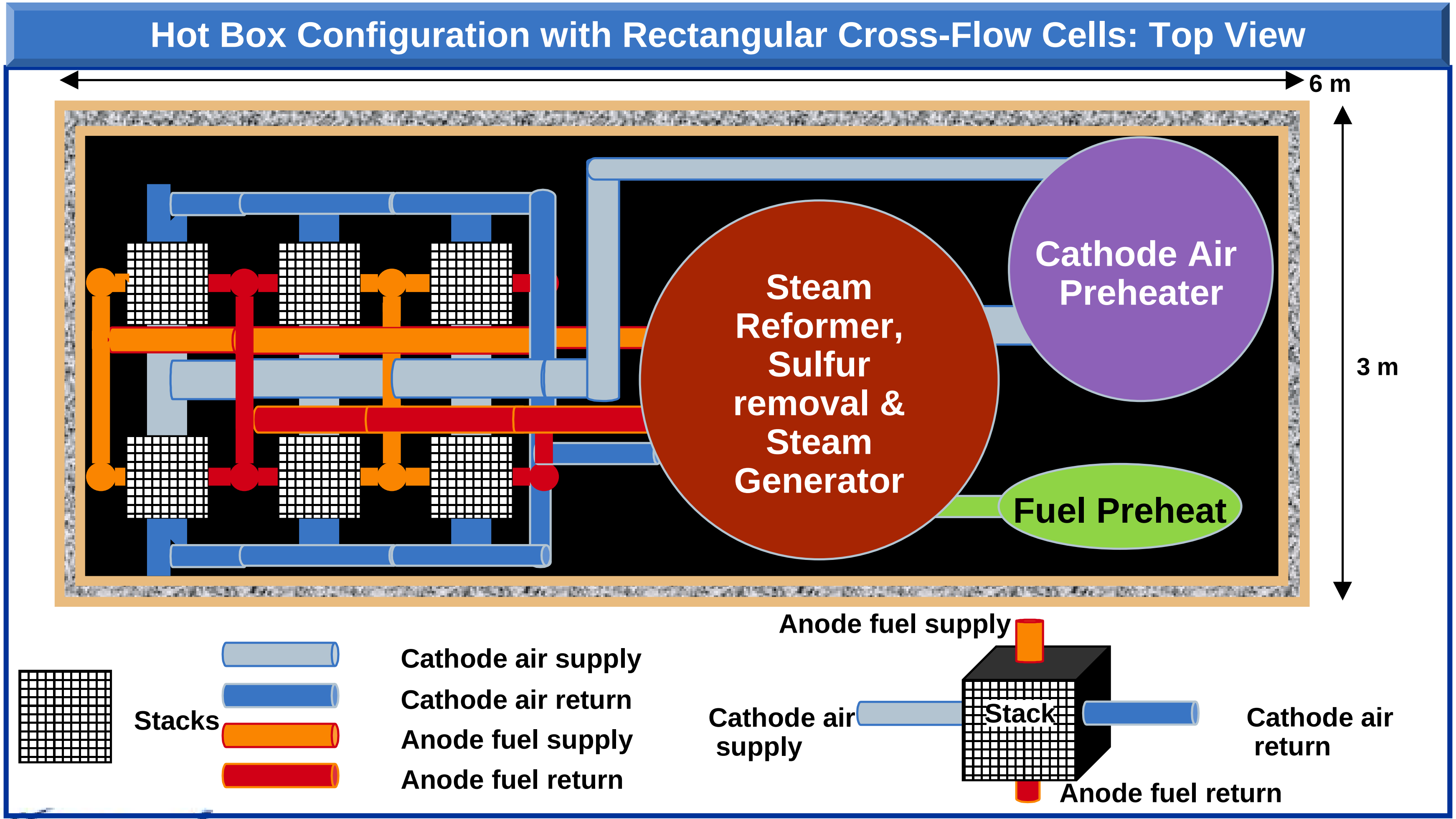
Key: Rating **+++** = Good Performance, **–** = Poor Performance

Report Topics

Manifolding can be decreased by providing a system that services multiple trains of fuel cells.

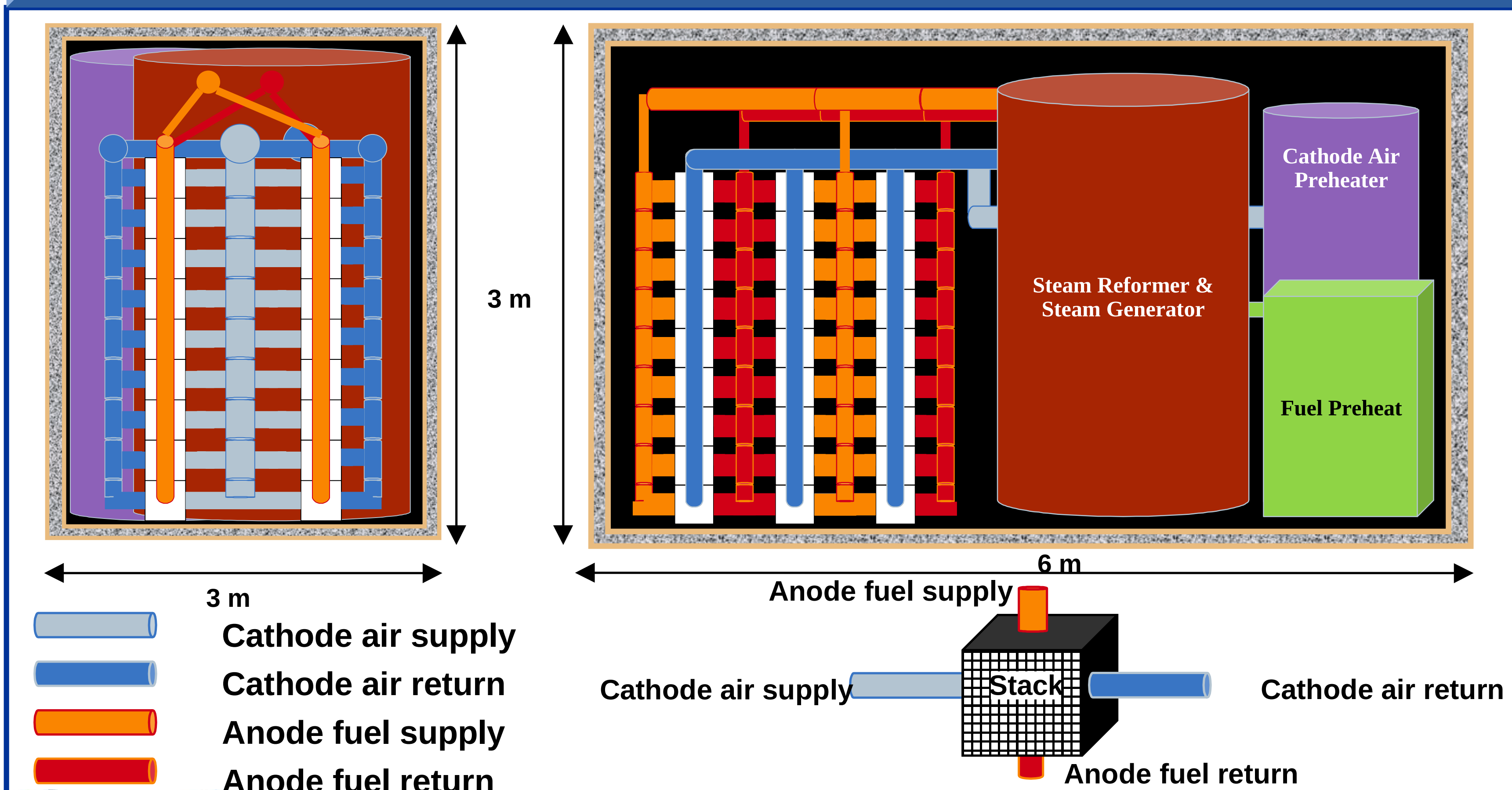


We developed a conceptual system design, to assess implications of manifolding and equipment interconnection.



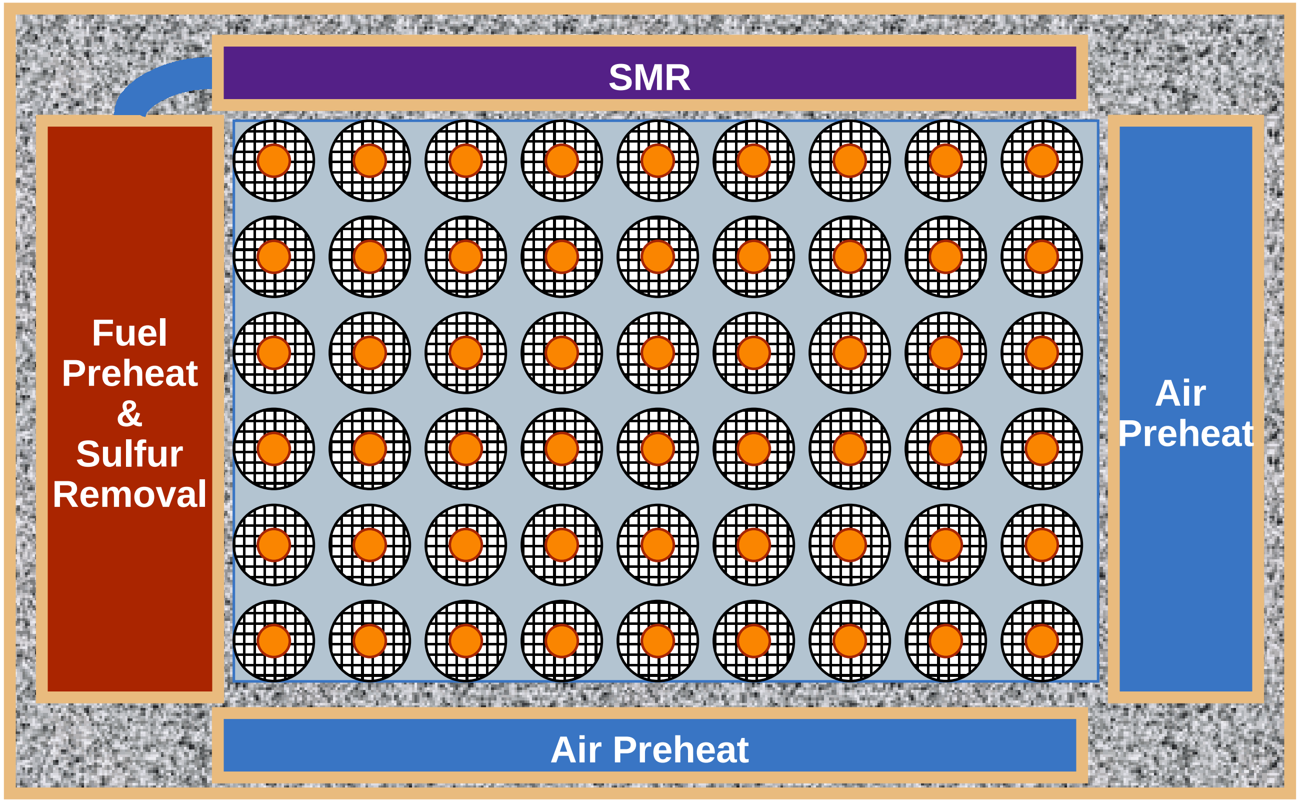
We limited integration to the reformer and air preheater, to maintain reasonable access.

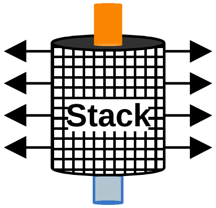
250-kW System Configuration: Side Views



With cylindrical stacks, a simpler manifolding arrangement may be feasible...

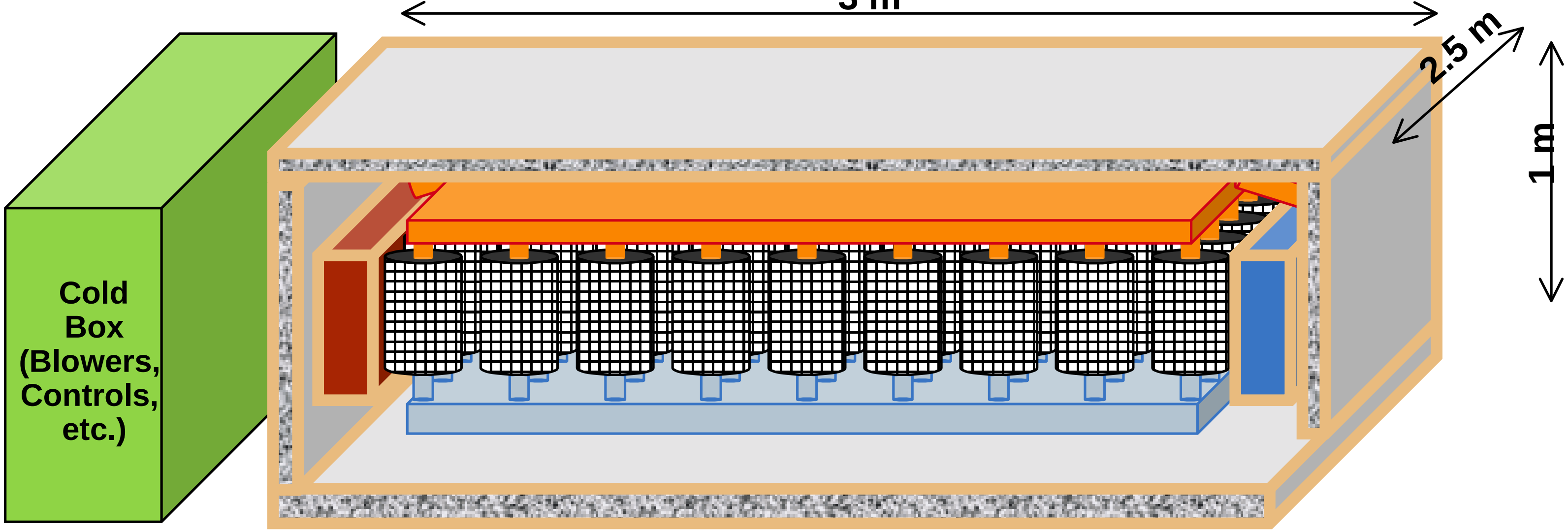
Hot Box Configuration with Radial-Outflow Cells: Top View





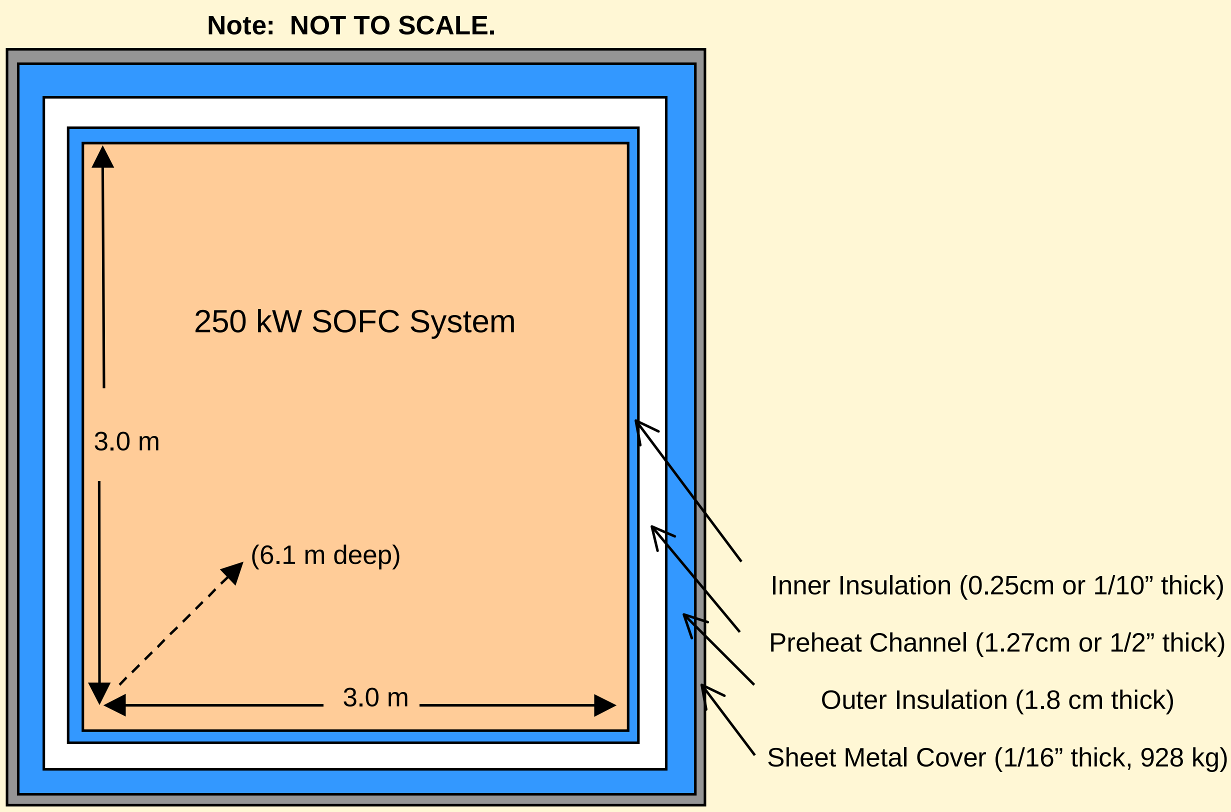
… resulting in a more compact overall design.

Hot Box Configuration with Radial-Outflow Cells: Side View



The entire SOFC system is enclosed in an insulated box with active cooling

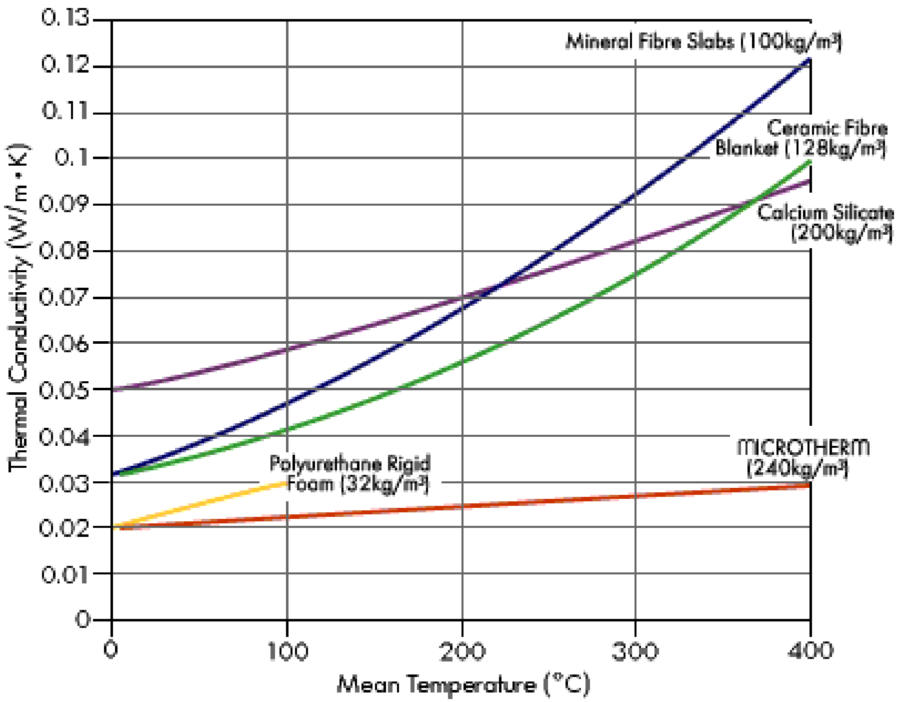
250-kW SOFC System Layout



This model predicts a total heat loss of 11.5-kW.

High temperature insulation was used to insulate the system box, with a second layer of cheaper, lighter, low temperature insulation on the exterior.

Insulation Properties		
Material	**Microtherm microporous silica**	**DOW Trymer 200 polyisocyanate**
Density (kg/m³)	**300**	**32.8**
Thermal Conductivity (W/m*K)	0.022 (T=100°C) 0.029 (T=400°C)	0.027 (T=24°C)
Maximum Temperature (°C)	1000	149
Volume Required	182 liters (54.6 kg)	1340 liters (44.0 kg)
Cost ($)	$5.2/liter	$2.6/liter



The system reliability will be a function of the reliability of the fuel cell stacks, which have the least associated history of operation.

- System reliability may be improved in two ways
  - Addition of redundancy in the system
  - Improvement of system components
- System reliability hinges mainly on the performance of the steam methane reformer and the fuel cell stacks
- The air blowers have field data showing that they run continuously without failure
  - This is based on data found in the Reliability Analysis Center's Nonelectric Parts Reliability Data and information obtained from the manufacturer
- The heat exchangers have similar field data showing that they run continuously without failure
  - This is based on data found in the Reliability Analysis Center's Nonelectric Parts Reliability Data and information obtained from the manufacturer
  - The heat exchangers are least prone to failure when run continuously as they are not subjected to the high thermal stresses encountered when heating up and cooling down across such a large temperature range
- The ZnO bed will be split into two separate units as one will be regenerating while the other is in use
  - If failure should occur, it can be addressed while the other unit is up and running

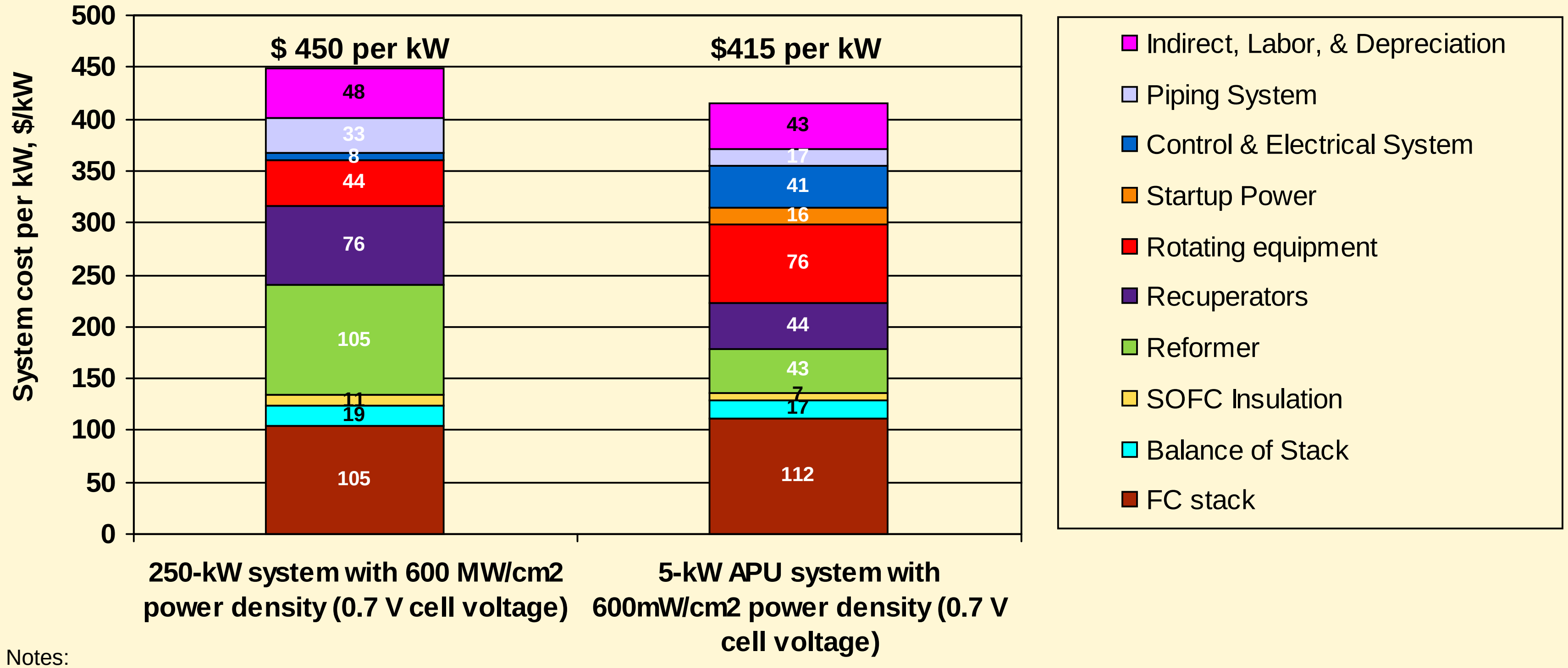
We used manufacturer quotes, component quotes and manufacturing models to estimate the system cost.

Component	Method of Estimation	Comments, What is not included
Tubular Steam Reformer system (including sulfur removal, reformer, and hydrogen supply for sulfur ZnO beds)	◆ The ZnO bed estimated by manufacturing model with 2 times required sorbent capacity (one online/one regenerating) ◆ The reformer was estimated based on catalyst space velocity; the weight of a vessel to encase the tubes was estimated; costs all based on weight of material; processing cost not included	◆ A hydrogen membrane to separate nominal hydrogen for the sulfur removal system & recycle compressor was not included ◆ Water conditioning for the steam reformer not included ◆ The reformer does not require shift beds and a CO clean-up device
Fuel cell stacks & packaging	◆ Fuel cell unit cells and stack estimated with existing TIAX planar solid oxide fuel cell manufacturing cost model using individual layer process flow ◆ Balance of stack (endplates, current collector, electrical insulator, outer wrap & tie bolts) estimated with manufacturing cost model ◆ Material costs for outer insulation and active cooling packaging estimated; processing not included; cost included for active air cooling blower	◆ Assumes anode supported cells (e.g. electrode supported planar cells) ◆ Assumed internal manifolding in stacks ◆ Packaging costs do not include any installation cost (e.g. labor and any foundations/footings required)
Heat exchangers	◆ The heat exchangers were estimated with a manufacturing cost model by costing the heat exchange in the form of coils incased by a shell (Similar to the method used in the SECA APU study)	◆ We had solicited quotes for the heat exchangers in the form of fin/plate heat exchangers. The manufacturer gave quotes for up to 200 units per year. The validity of extrapolating to 10,000 units per year is suspect

We used manufacturer quotes, component quotes and manufacturing models to estimate the system cost.

Component	Method of Estimation	Comments, What is not included
Rotating Equipment	◆ Pumps, blowers & compressors were estimated with manufacturers quotes and vendor quotes	◆ The hydrogen recycle compressor was not included ◆ A quote for the natural gas compressor was not obtained; cost estimated with comparable air compressor
System Controls	◆ We used the same cost per kW as was used in the SECA APU study	◆ Control & electrical system included system sensors, controls, system logic and safety contactor
System piping	◆ Estimates were made for runs of piping connecting the major pieces of equipment	◆ Does not include installation (e.g. labor & materials)
Grid interconnect	◆ We estimated the efficiency losses in converting the power to AC voltage	◆ Does not included grid interconnect associated cost ◆ Cost of power conditioning not included

Because of the larger scale, the cost of the 250 kW system is less than 10% higher than that of the 5 kW POX unit, despite 10% higher efficiency.



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 jacket
5. The reformer includes cost for the steam reformer and 2 zinc oxide beds
6. The recuperator includes the cathode heat exchanger, steam generator and fuel preheat
7. Rotating equipment includes cathode air blower, water pump, active air cooling blower and natural gas compressor
8. Indirect, Labor, and Depreciation includes all indirect costs, labor costs, and depreciation on equipment, tooling, and buildings
9. The absolute error of the estimate is 30-40 percent.

The main differences between the 250-kW modular system and the 5-kW system studied previously is in the reformer used and its impact on BOP.

- Similar power density and cell voltage leads to similar cost per kW for the fuel cell stacks
- The increased cost of the 250-kW system is in using a more efficient steam methane reformer
  - The cost of the reformer involves cost of catalyst tubes, steam reforming catalyst, burners, the shell vessel and associated piping & instrumentation
  - A POX reformer is much less complex than a steam reformer (and less efficient)
- Using spent anode fuel for the steam reformer has implications for the BOP
  - A lower temperature exhaust is available to provide enthalpy for steam, fuel and air preheat (lower approach temperatures results in higher heat exchange areas)
- There are avenues to reduce cost which were not explored in this study
  - Fresh fuel could be used to provide SMR energy
  - Anode exhaust could then be used to provide energy for heat exchange (higher approach temperatures feasible)
  - The steam reformer could be run at lower conversion resulting in higher exhaust temperatures
- Rotating equipment is cheaper for the 250-kW system because of capacity and type
  - Larger capacity equipment are cheaper on a per kW basis
  - The SMR system did not recover water for steam generation so that an air blower could be used instead of a compressor
- Piping is more expensive in the 250-kW system because less integration of process units was used resulting in more manifolding
- The active cooling system of the 250-kW system is more expensive mainly in the use of a higher capacity blower to aid in reducing insulation volume

Report Topics

It is feasible to combine small 5-kW units for larger DG applications of ~250-kW.

- The 250-kW system made up of 5-kW units benefits from economy of scale: resulting in improved system efficiency (50%):
  - SMR reformer*
  - lower heat loss
- Increasing single stack capacity would drastically reduce manifolding requirements (and associated footprint)
- Integration with a gas turbine combined cycle system would require single train

* Though water partial pressure at anode may lead to lower fuel utilization, overall effect is not clear now

With SECA stack technology, a highly attractive $400 - $500 /kW* system with 50% efficiency appears feasible.

- The 250-kW system made up of 5-kW units benefits from economy of scale: resulting in cost savings (down to around $450/kW) through:
  - Shared Bop components, especially controls and rotating equipment
  - Low cost for cooling, heat exchangers, compared with comparable 5 kW system
- Further cost reduction may be possible by reducing system efficiency requirements:
  - Less heat integration which would reduce heat exchange requirements but require additional fuel consumption
  - Use a less expensive reformer (e.g. ATR or POX) with lower efficiency
- Lower manufacturing volume for BOP (in numbers) partially off-sets the cost reduction through economy of scale of the equipment
- Increasing single stack capacity would drastically reduce manifolding requirements (and associated footprint and expense)
- The cost of $500-600 per kW for a 50% efficient system is likely to be highly attractive in a wide range of stationary and possibly mobile applications

* Exclusive of power electronics

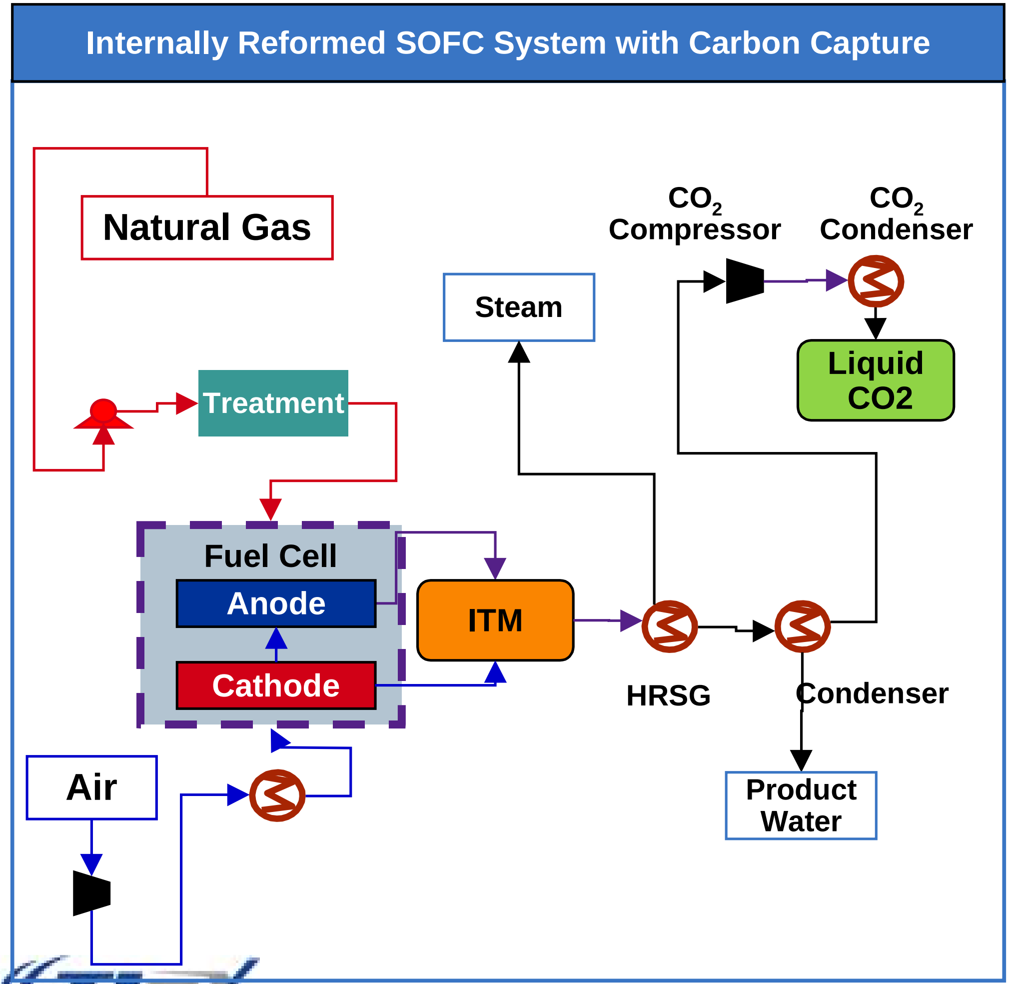
Report Topics

NETL wants to understand the feasibility, footprint, efficiency and R&D needs for a 20-MW total carbon sequestration modular SECA SOFC system.

- The idea:
  - 20 MW electric simple-cycle atmospheric SOFC power system
  - Based on 5 kW SECA planar anode-supported SOFC stack modules
  - Assume natural gas fuel and 100% internal reforming
  - Stack performance consistent with previous ADL study
  - Co-production of steam, water
  - 100% sequestration of carbon as liquid CO_2
- NETL's question was: "Is this a good idea?" :
  - What is the likely efficiency of such a system using 5-kW fuel cell stacks?
  - What are likely water and steam production rates?
  - What are the main parasitic loads?
  - What would the layout be and the associated footprint?
  - What are the main R&D needs for such a system?
  - What are the balance of plant requirements?
  - Can recycle of spent natural gas fuel be used to boost efficiency?

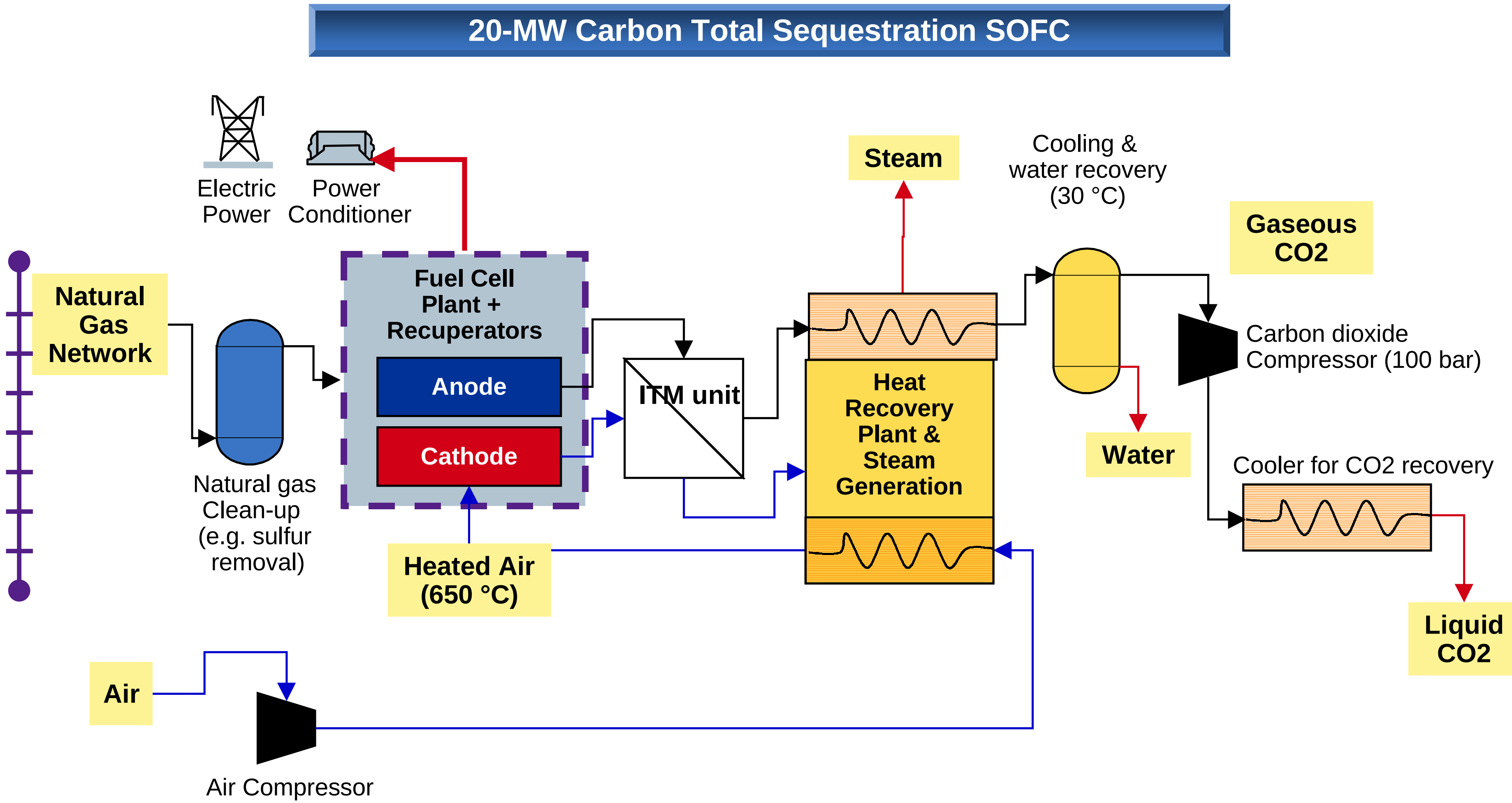
NETL wanted a quick high-level analysis of this technology concept.

The basic concept was outlined by NETL; an ion transport membrane (ITM) is used for conversion of residual methane to allow heat recovery.



- Fuel cell converts most of methane (~80-90%) and generates power
- Residual methane is converted to CO_2 for capture using an ITM, with the cathode air as an O_2 source, providing additional heat
- HSRG and Condenser used for heat recovery (co-gen steam) and product water separation
- Dry CO_2 is compressed and cooled to produce liquid CO_2.,
- Pressure is high enough to ensure contaminants are dissolved in the liquid CO_2
- No fuel recycle

The system could have an electrical efficiency of 40 - 46 % efficiency and lead to a relatively simple system.



A HYSYS model was used to estimate rotating equipment, heat exchanger requirements and likely water and steam production rates.

- A simplified analysis was used for the thermodynamic model
- A fully internal reforming planar solid oxide fuel cell stack was assumed with internal manifolding of reactants
  - 5-kW stacks
  - The stack is isothermal and operates at 800ºC
  - The stack operates at 0.75V with 85 percent fuel utilization (single-pass)
  - A power density of 0.6 W per cm^2 was assumed (Aggressive case)
  - The stack is air-cooled with a maximum thermal temperature gradient of 150ºC
- The anode exhaust can then be compressed and cooled to drop out a fraction of the CO_2 for recovery
- Subsequent recovery of the CO_2 in the gaseous stream will require a standard acid gas removal technology such as an amine or solvent based system

Despite the relative simplicity of the concept, quite a few additional components are required for the CO_2 capture.

Gas Processing	Fuel Cell & ITM	Recuperators	Rotating Equipment	Balance of Plant	Carbon Capture
◆ Sulfur removal system for pipeline natural gas	◆ Fuel Cell Stack (Unit Cells) [1] ◆ Balance of Stack[2] ◆ Fuel cell module plant packaging and insulation ◆ Manifolding for stacks ◆ Power conditioner ◆ Fuel cell assumed to be capable of internally reforming natural gas fuel ◆ ITM units closely coupled with SOFC	◆ Anode exhaust gas cooler (used to preheat natural gas) ◆ Depleted cathode air heat recovery unit (used to preheat fresh cathode air) ◆ Steam generator	◆ Air compressor ◆ CO2 rich stream compressor ◆ Recycle Compressor	◆ Startup power ➢ Start-up battery ➢ Blower for active cooling ➢ Switching regulator for recharging ◆ Control & electrical system ➢ System sensors ➢ Controls ➢ System logic ➢ Safety contactor ◆ System piping ◆ System insulation ◆ Water conditioning (product water is likely to be acid)	◆ [CO2 compressor in rotating equipment] ◆ Water drop-out for anode gas ◆ Cooler for compressed CO_2 rich stream from anode exhaust for liquid CO2 recovery

1. The fuel cell stack includes cathode, anode, electrolyte, interconnects, and layer assembly, and stack assembly
2. The balance of stack includes endplates, current collector, electrical insulator, outer wrap, and tie bolts. It is assumed that the stack is internally manifolded.

The electrical efficiency (based on AC power and HHV) of this system is expected to range from 40 to 47%, HHV.

	Base Case-20-MW net	High utilization and voltage	Low cell voltage	Parasitics Increased
Overall efficiency (AC & HHV)	43%	47%	40%	40%
Parasitic Power	3.3 MW	3.3 MW	3.3MW	5 MW
Cell Voltage	0.75 V	0.75 V	0.7 V	0.75 V
Fuel Utilization	85%	90%	85%	85%
Power electronics	95%	95%	95%	95%
Waste Heat Recoverable	14 MW	10 MW	17 MW	17 MW

The biggest part of the plant will be the fuel cell module plant with a total plant layout of ~200 to 210 m2.

Parasitics

- Air requirements ~5-6 excess (includes stoichiometric air and cooling air with inlet cathode temperature of 650°C)
- Air compression up to 1.5 bara: 2.3MW with 80% efficient electrically driven compressor
- CO_2 compression up to 100 bar: 1 MW with 75% efficient compressor

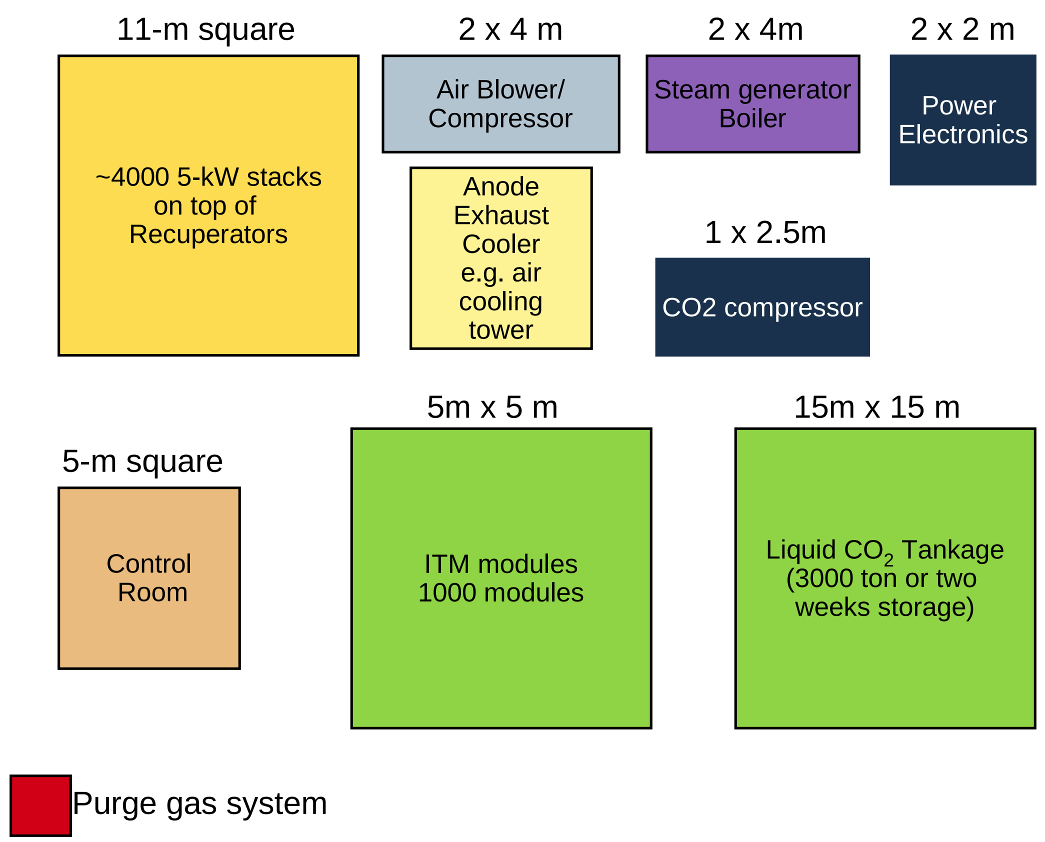
Steam & Water production

- 20 bar steam at 80% recovery of waste heat: 21,000 kg per hour steam
- Water recovery at 95% of produced water: 5,500 kg per hour liquid water

With recovery of product water approximately around 3,000 kg/h water can be produced.

Our preliminary estimates show that the footprint of the system equipment would be around 400 m², with a total plant area of around 1000 m².

Plot Layout of 20-MW SECA System with Carbon Capture



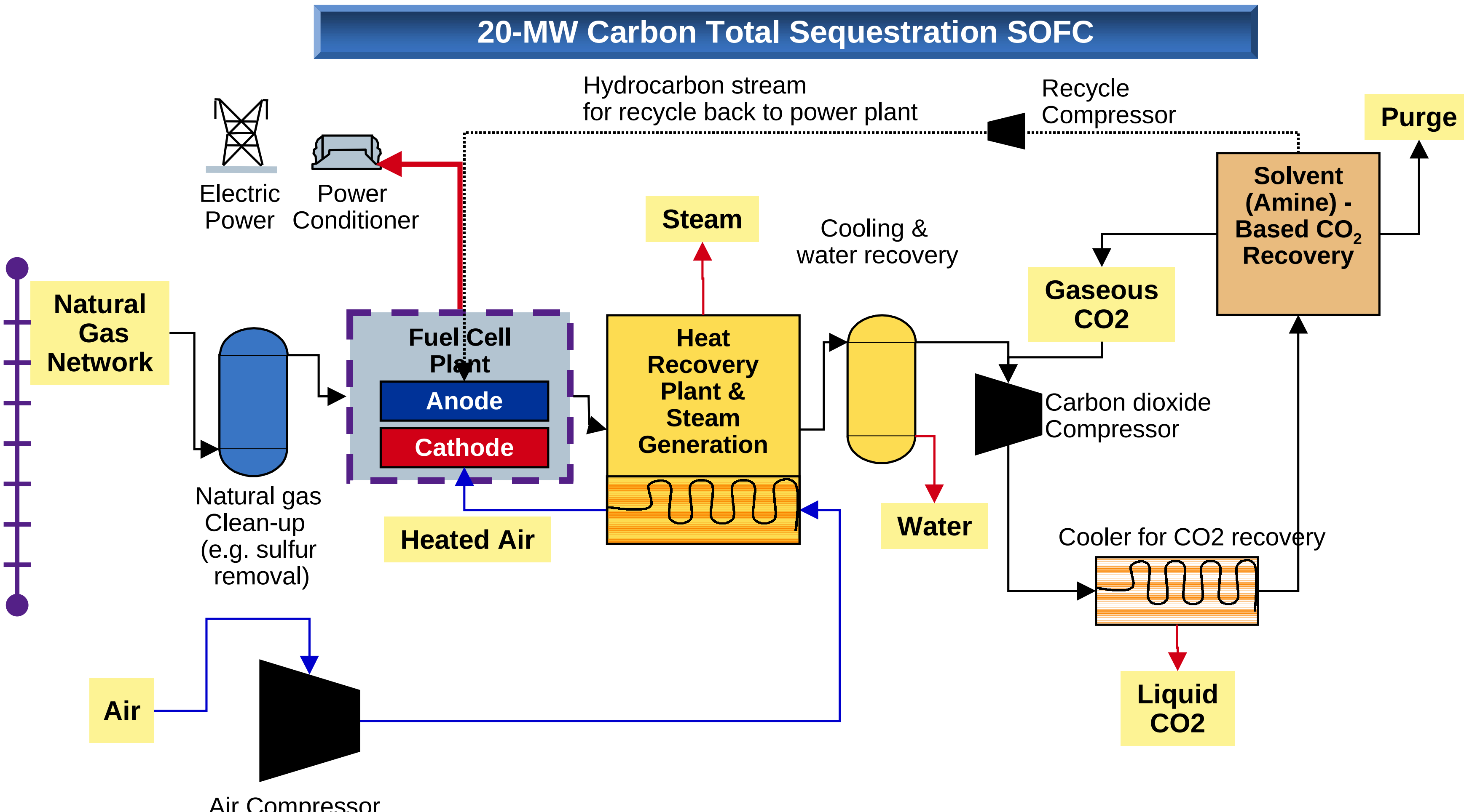
Comments

- The fuel cell stacks are placed on two levels on top of the heat; the system is then packaged and insulated
- ITM are in similar configuration as SOFC stack, but 1/4 size
- 1- stage centrifugal air compressor
- It is likely that steam generation in HRSG from air and anode gas condenser combined
- The carbon dioxide compressor (up to 100 bar (1500 psi) will require 4-5 stages
- CO_2 Storage for two weeks' of production

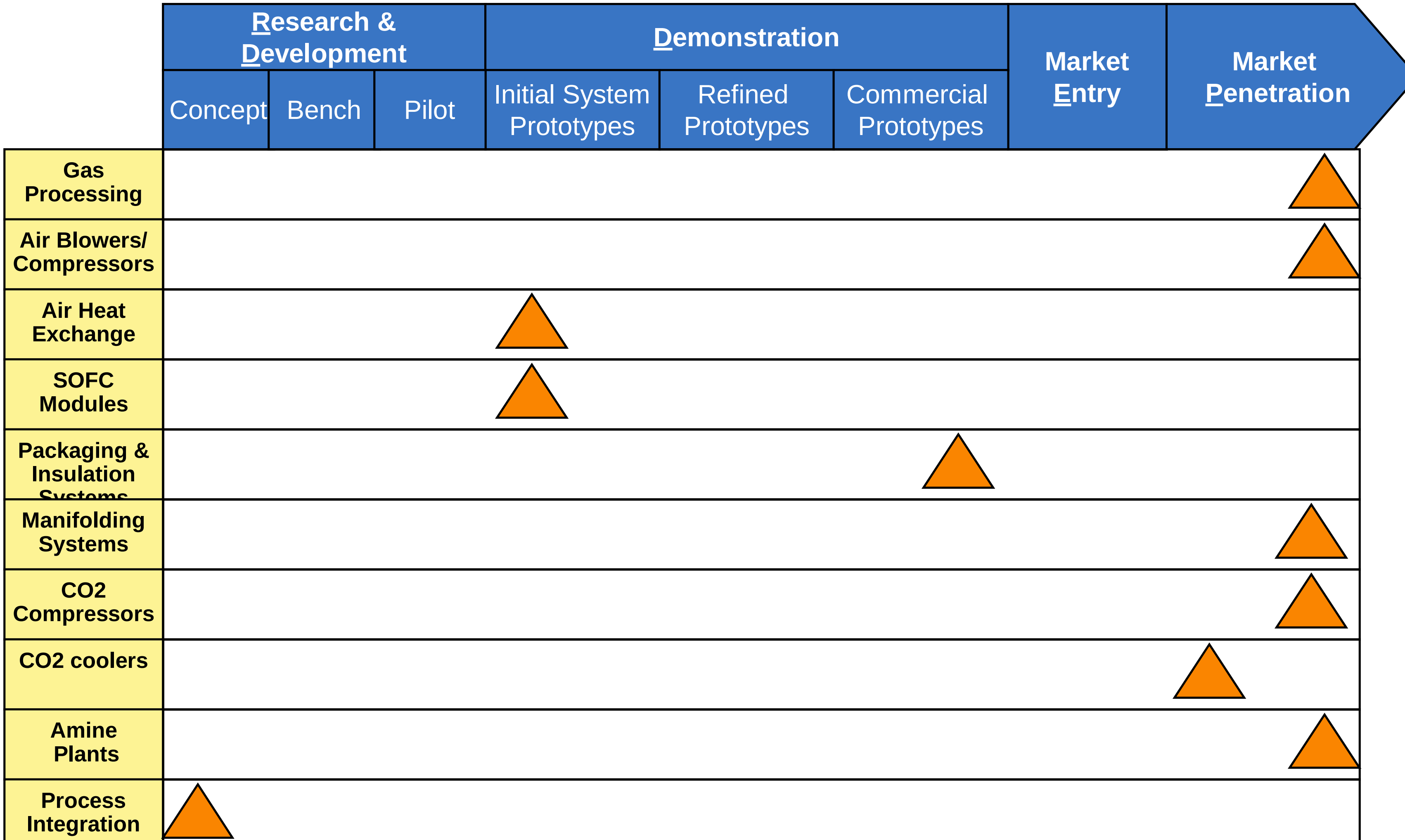
An alternative approach would separate the residual methane from the CO_2, thus improving the efficiency of the process.

- In the ITM, not all residual fuel will be converted, and only thermal energy can be recovered.
- Any non-CO_2 gases must be co-condensed, which is not a problem as long as it is compatible with the ultimate disposition of the CO_2

We modified the PFD to incorporate fuel recycle and eliminate the ITM, resulting in a more complex system, but with around 50+% electrical efficiency.



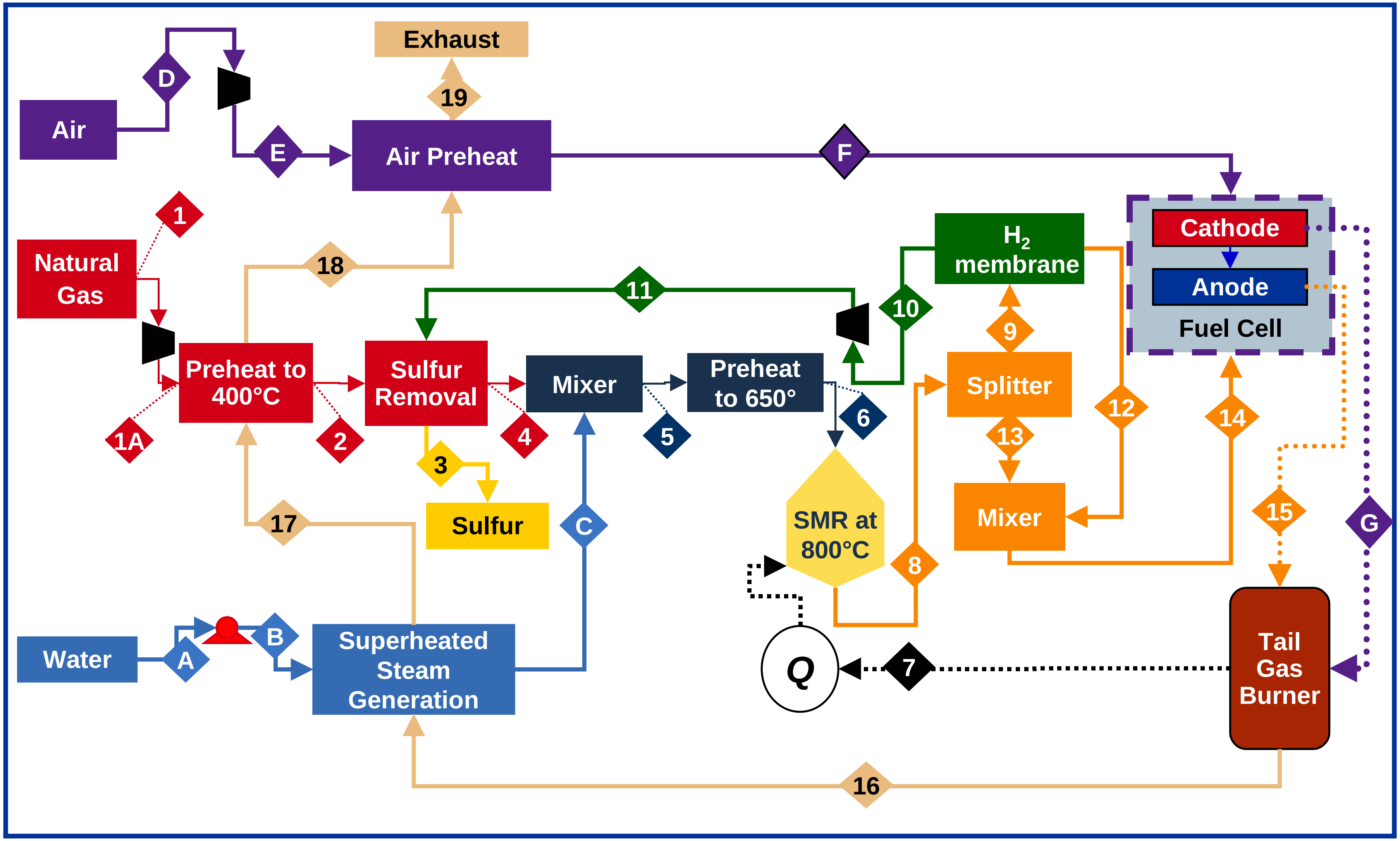
Process integration and optimization, along with fuel cell and recuperator development are the key R&D topics to be addressed.



Process integration and evaluation of CO_2/Methane mixture behavior during sequestration and storage appear the key topics for research.

- Evaluate various process configurations:
  - Fuel recycle or not
  - ITM or not
  - Integration of alternative CO_2 removal methods (for efficiency and purity)
  - Integration of other power cycles or not
- In the current options considered, the liquid CO_2 will have appreciable amounts of dissolved methane and other gases.
- The effects of this contamination on potential CO_2 disposition options must be evaluated

250 kW SOFC Base Case Process Flow Sheet



Pump, Compressor and Heat Exchanger Properties

Pumps and Compressors	Efficiency	Duty (kW)	Pressure Head (m)
Natural Gas Compressor	75%	0.33	2573
Water Pump	75%	$1.0e^{-3}$	2
Active Cooling Air Compressor	75%	18.9	1125

Heat Exchangers	UA (kJ/C-h)	LMTD	Duty (kW)
Fuel Preheat	81	458 °C	10
Superheated Steam Generator	1020	408 °C	116
Fuel and Steam Preheat	396	145 °C	16
Cathode Air Preheat	35100	63 °C	611

1. 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.
2. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)
3. 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.

System Flow Sheet Base Case Results with Active Cooling

Property	Component	Unit	1-Raw NG	1A-comp NG	2-NG to ZnO Bed	3-Sulfur Stream	4-Desulfur-ized Gas	5-NG & Steam to Preheat	6-NG & Steam to SMR	7-Energy for SMR	8-SMR Effluent
Molar Flow		kgmole/h	2.20	2.20	2.20	4.40E-04	2.20	8.80	8.80		12.00
Mass Flow		kg/s	0.01	0.01	0.01	0.00	0.01	0.04	0.04		0.04
Temperature		C	20.00	35.02	400.00	400.00	400.00	488.79	638.00		800.00
Pressure		bar	1.05	1.24	1.22	1.10	1.12	1.09	1.09		1.09
Molecular Weight		<none>	16.04	16.04	16.04	17.04	16.04	17.52	17.52		12.85
Heat Flow		kJ/h	-1.65E+05	-1.64E+05	-1.27E+05	-5.91E+01	-1.27E+05	-1.60E+06	-1.54E+06	1.14E+02	-1.13E+06
Lower Heat Value		kJ/kgmole	8.03E+05	8.03E+05	8.03E+05	1.21E+05	8.03E+05	2.01E+05	2.01E+05		<empty>
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	Hydrogen		0.00	0.00	0.00	0.50	0.00	0.00	0.00		0.46
	Oxygen		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	Nitrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	H2O		0.00	0.00	0.00	0.00	0.00	0.75	0.75		0.36
	CO2		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.06
	CO		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.07
	Methane		1.00	1.00	1.00	0.00	1.00	0.25	0.25		0.05
	S_Rhombic		0.00	0.00	0.00	0.50	0.00	0.00	0.00		0.00

Property	Component	Unit	9-to H2 Membrane	10-H2 to Compres-sor	11-H2 to ZnO Bed	12-CO Recycle	13-Fuel to Mixer	14-Fuel to Anode	15-Anode Exhaust to TGB	16-Hot Stream for Superheat-ing Steam	17-Hot Stream for NG
Molar Flow		kgmole/h	4.79E-04	2.20E-04	2.20E-04	2.59E-04	12.00	12.00	13.20	168.80	168.80
Mass Flow		kg/s	0.00	0.00	0.00	0.00	0.04	0.04	0.08	1.33	1.33
Temperature		C	662.00	662.00	650.00	662.00	662.00	662.00	800.00	775.52	703.03
Pressure		bar	1.09	1.09	1.24	1.09	1.09	1.09	1.08	1.08	1.07
Molecular Weight		<none>	12.85	2.02	2.02	22.06	12.85	12.85	21.07	28.26	28.26
Heat Flow		kJ/h	0.00E+00	4.11E+00	4.04E+00	-5.18E+01	-1.19E+06	-1.19E+06	-2.86E+06	4.98E+05	8.16E+04
Lower Heat Value		kJ/kgmole	<empty>	2.42E+05	2.42E+05	<empty>	<empty>	<empty>	<empty>	1.29E-05	1.29E-05
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hydrogen		0.46	1.00	1.00	0.00	0.46	0.46	0.07	0.00	0.00
	Oxygen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.17
	Nitrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.75	0.75
	H2O		0.36	0.00	0.00	0.66	0.36	0.36	0.77	0.07	0.07
	CO2		0.06	0.00	0.00	0.11	0.06	0.06	0.15	0.01	0.01
	CO		0.07	0.00	0.00	0.14	0.07	0.07	0.01	0.00	0.00
	Methane		0.05	0.00	0.00	0.09	0.05	0.05	0.00	0.00	0.00
	S_Rhombic		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

System Flow Sheet Base Case Results with Active Cooling

		Stream	18-Hot Stream for Cathode Air	19-Exhaust	A-Water	B-Compres-sed Water	C-Super-heated Steam	D-Ambient Air	E-Compres-sed Air	E-Cathode Air In	G-Depleted Cathode Air
Property	Component	Unit									
Molar Flow		kgmole/h	168.80	168.80	6.60	6.60	6.60	160.00	160.00	160.00	156.13
Mass Flow		kg/s	1.33	1.33	0.03	0.03	0.03	1.28	1.28	1.28	1.25
Temperature		C	696.54	293.20	21.00	21.00	534.00	10.00	24.61	650.00	799.44
Pressure		bar	1.07	1.04	1.01	1.24	1.09	1.04	1.19	1.16	1.08
Molecular Weight		<none>	28.26	28.26	18.02	18.02	18.02	28.85	28.85	28.85	28.77
Heat Flow		kJ/h	4.46E+04	-2.16E+06	-1.89E+06	-1.89E+06	-1.47E+06	-7.13E+04	-3.37E+03	3.07E+06	3.76E+06
Lower Heat Value		kJ/kgmole	1.29E-05	1.29E-05	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00	0.00E+00
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hydrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Oxygen		0.17	0.17	0.00	0.00	0.00	0.21	0.21	0.21	0.19
	Nitrogen		0.75	0.75	0.00	0.00	0.00	0.79	0.79	0.79	0.81
	H2O		0.07	0.07	1.00	1.00	1.00	0.00	0.00	0.00	0.00
	CO2		0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CO		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Methane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	S_Rhombic		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

System Flow Sheet 10% Recycle of Depleted Cathode Air Results

		Stream	1-Raw NG	1A-comp NG	2-NG to ZnO Bed	3-Sulfur Stream	4-Desulfur-ized Gas	5-NG & Steam to Preheat	6-NG & Steam to SMR	7-Energy for SMR	8-SMR Effluent
Property	Component	Unit									
Molar Flow		kgmole/h	2.25	2.25	2.25	0.00	2.25	9.00	9.00		12.28
Mass Flow		kg/s	0.01	0.01	0.01	0.00	0.01	0.04	0.04		0.04
Temperature		C	20.00	35.01	400.00	400.00	400.00	488.79	638.00		800.00
Pressure		bar	1.05	1.24	1.22	1.10	1.12	1.09	1.09		1.09
Molecular Weight		<none>	16.04	16.04	16.04	17.04	16.04	17.52	17.52		12.84
Heat Flow		kJ/h	-1.69E+05	-1.68E+05	-1.30E+05	-6.04E+01	-1.30E+05	-1.63E+06	-1.57E+06	1.15E+02	-1.16E+06
Lower Heat Value		kJ/kgmole	802622.7297	802622.7297	802566.6672	120970.9956	802703	200675.75	200675.75		<empty>
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	Hydrogen		0.00	0.00	0.00	0.50	0.00	0.00	0.00		0.46
	Oxygen		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	Nitrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.00
	H2O		0.00	0.00	0.00	0.00	0.00	0.75	0.75		0.36
	CO2		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.06
	CO		0.00	0.00	0.00	0.00	0.00	0.00	0.00		0.07
	Methane		1.00	1.00	1.00	0.00	1.00	0.25	0.25		0.05
	S_Rhombic		1.00E-04	1.00E-04	1.00E-04	0.5	0	0	0		0

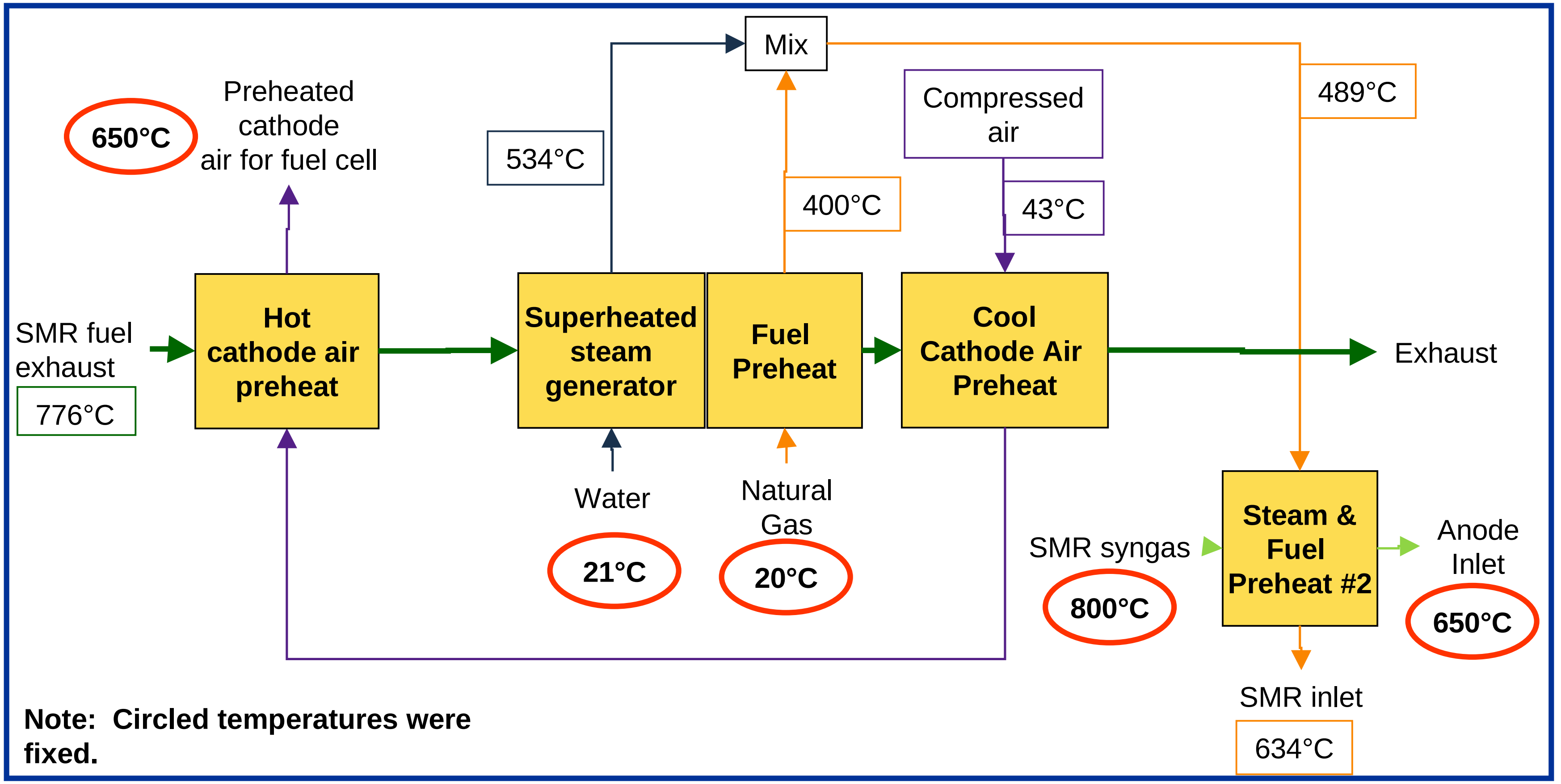
		Stream	9-to H2 Membrane	10-H2 to Compres-sor	11-H2 to ZnO Bed	12-CO Recycle	13-Fuel to Mixer	14-Fuel to Anode	15-Anode Exhaust to TGB	16-Hot Stream for Superheat-ing Steam	17-Hot Stream for NG
Property	Component	Unit									
Molar Flow		kgmole/h	0.00	0.00	0.00	0.00	12.28	12.28	13.50	156.00	156.00
Mass Flow		kg/s	0.00	0.00	0.00	0.00	0.04	0.04	0.08	1.22	1.22
Temperature		C	662.00	662.00	650.00	662.00	662.00	662.00	800.00	773.32	693.20
Pressure		bar	1.09	1.09	1.24	1.09	1.09	1.09	1.08	1.08	1.07
Molecular Weight		<none>	12.84	2.02	2.02	22.07	12.84	12.84	21.07	28.20	28.20
Heat Flow		kJ/h	0.00E+00	4.21E+00	4.13E+00	-5.29E+01	-1.22E+06	-1.22E+06	-2.93E+06	1.09E+05	-3.17E+05
Lower Heat Value		kJ/kgmole	<empty>	2.42E+05	2.42E+05	<empty>	<empty>	<empty>	<empty>	1.36E-05	1.36E-05
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hydrogen		0.46	1.00	1.00	0.00	0.46	0.46	0.07	0.00	0.00
	Oxygen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.17	0.17
	Nitrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.74	0.74
	H2O		0.36	0.00	0.00	0.66	0.36	0.36	0.77	0.07	0.07
	CO2		0.06	0.00	0.00	0.11	0.06	0.06	0.15	0.01	0.01
	CO		0.07	0.00	0.00	0.14	0.07	0.07	0.01	0.00	0.00
	Methane		0.05	0.00	0.00	0.09	0.05	0.05	0.00	0.00	0.00
	S_Rhombic		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

System Flow Sheet 10% Recycle of Depleted Cathode Air Results

		Stream	18-Hot Stream for Cathode Air	19-Exhaust	A-Water	B-Compres-sed Water	C-Super-heated Steam	D-Ambient Air	E-Compres-sed Air	F-Cathode Air In	G-Depleted Cathode Air
Property	Component	Unit									
Molar Flow		kgmole/h	156.00	156.00	6.75	6.75	6.75	147.00	147.00	147.00	143.04
Mass Flow		kg/s	1.22	1.22	0.03	0.03	0.03	1.18	1.18	1.18	1.14
Temperature		C	686.02	296.00	21.00	21.00	534.00	10.00	88.30	650.00	799.70
Pressure		bar	1.07	1.04	1.01	1.24	1.09	1.01	1.18	1.19	1.08
Molecular Weight		<none>	28.20	28.20	18.02	18.02	18.02	28.85	28.85	28.85	28.76
Heat Flow		kJ/h	-3.54E+05	-2.32E+06	-1.93E+06	-1.93E+06	-1.50E+06	-6.55E+04	2.71E+05	2.82E+06	3.45E+06
Lower Heat Value		kJ/kgmole	1.36E-05	1.36E-05	0	0	0	0	0	0	0
Component Molar Fraction	H2S		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Hydrogen		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Oxygen		0.17	0.17	0.00	0.00	0.00	0.21	0.21	0.21	0.19
	Nitrogen		0.74	0.74	0.00	0.00	0.00	0.79	0.79	0.79	0.81
	H2O		0.07	0.07	1.00	1.00	1.00	0.00	0.00	0.00	0.00
	CO2		0.01	0.01	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	CO		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	Methane		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00
	S_Rhombic		0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00	0.00

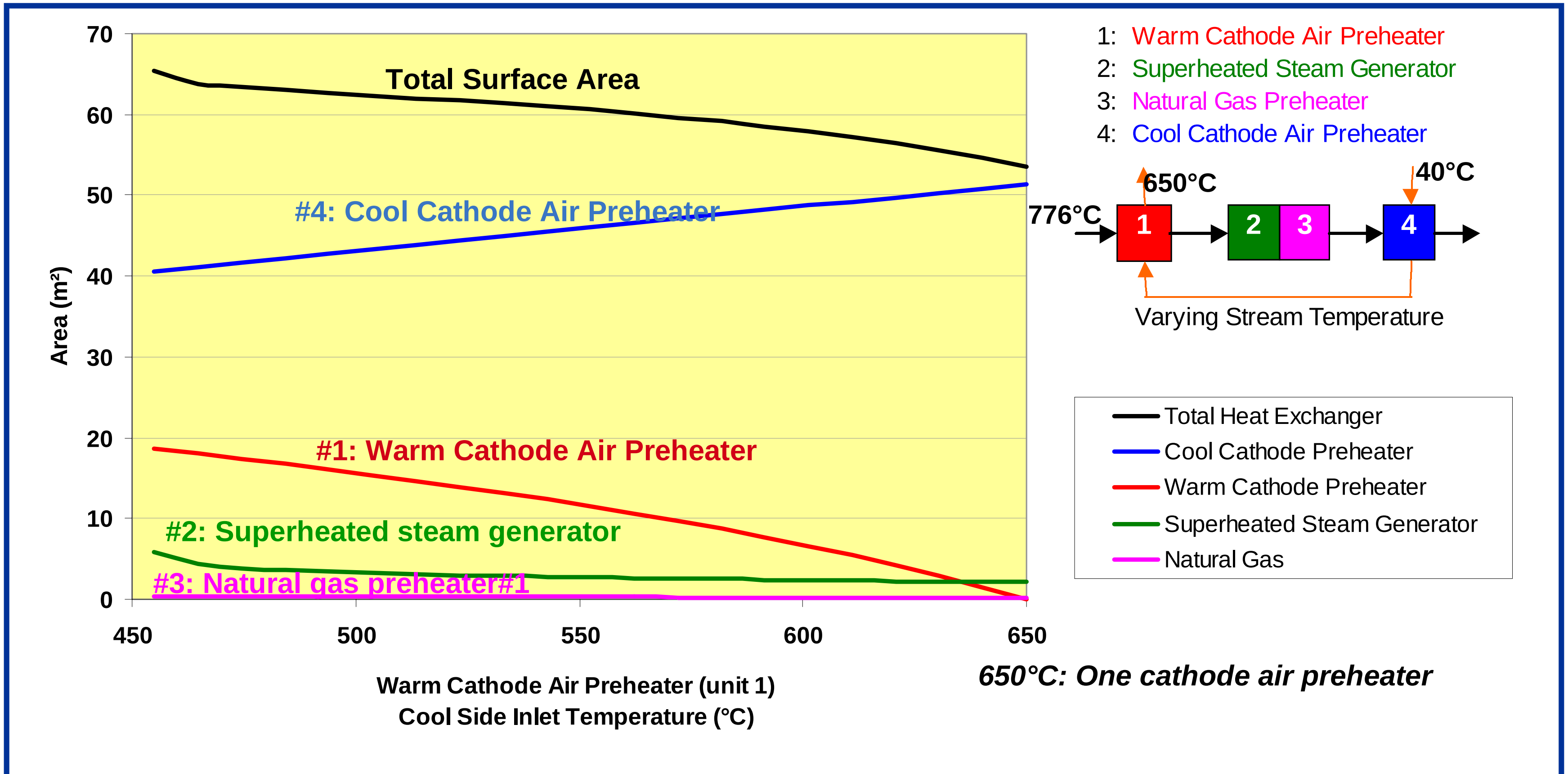
A	Thermodynamic Model Results
B	Alternative Process Diagrams
C	Component Design

We examined the possibility of splitting the cathode air preheater into two units, with the intent of minimized total surface area and cost.



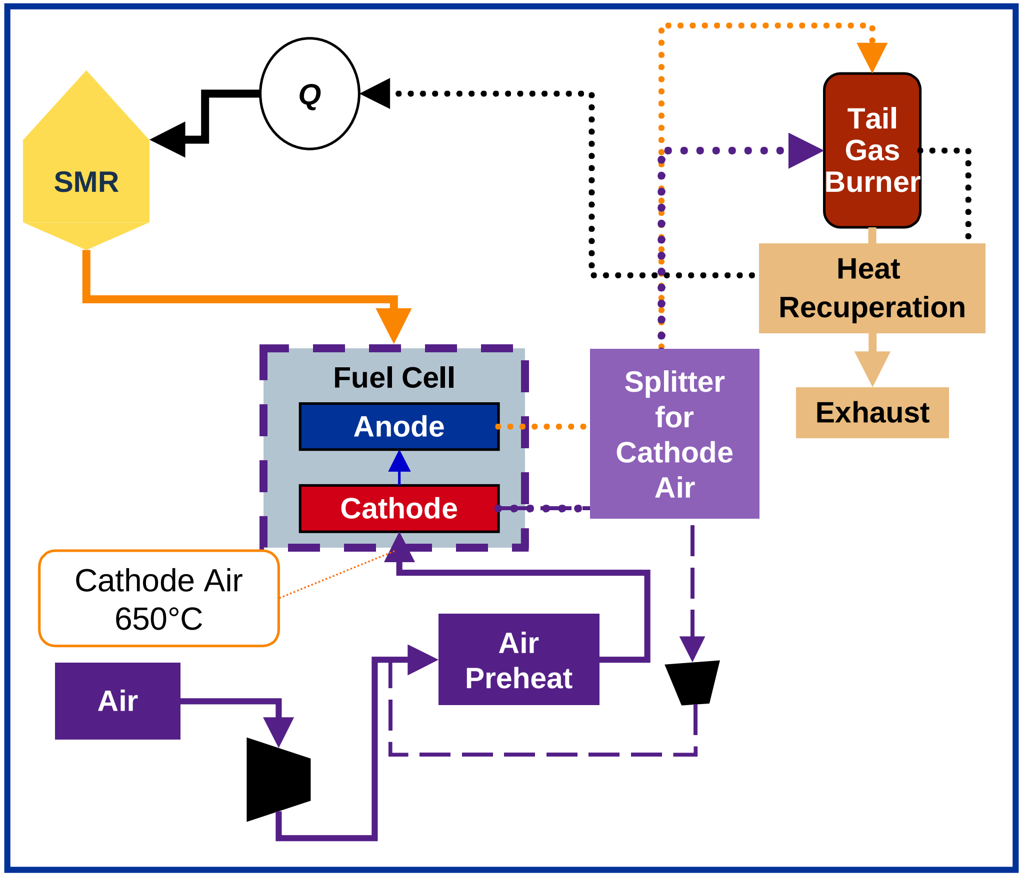
Note: Circled temperatures were fixed.

Total required heat exchanger area is minimized when the cathode air pre-heater is a single unit located downstream of the natural gas preheater#1.



1. The fresh cathode air is heated from 40°C to 650°C. The “cold side” inlet temperature of unit 1 is limited to ~450°C so that enough exhaust temperature is available for heating the rest of the feed streams
2. All data points are for two cathode air heat exchange units with varying inlet temperatures with the exception of the data for 650°C which describes a single unit for cathode air preheat

Cathode air compression requirements could be decreased by recycling a portion of the depleted cathode air back to the cathode.



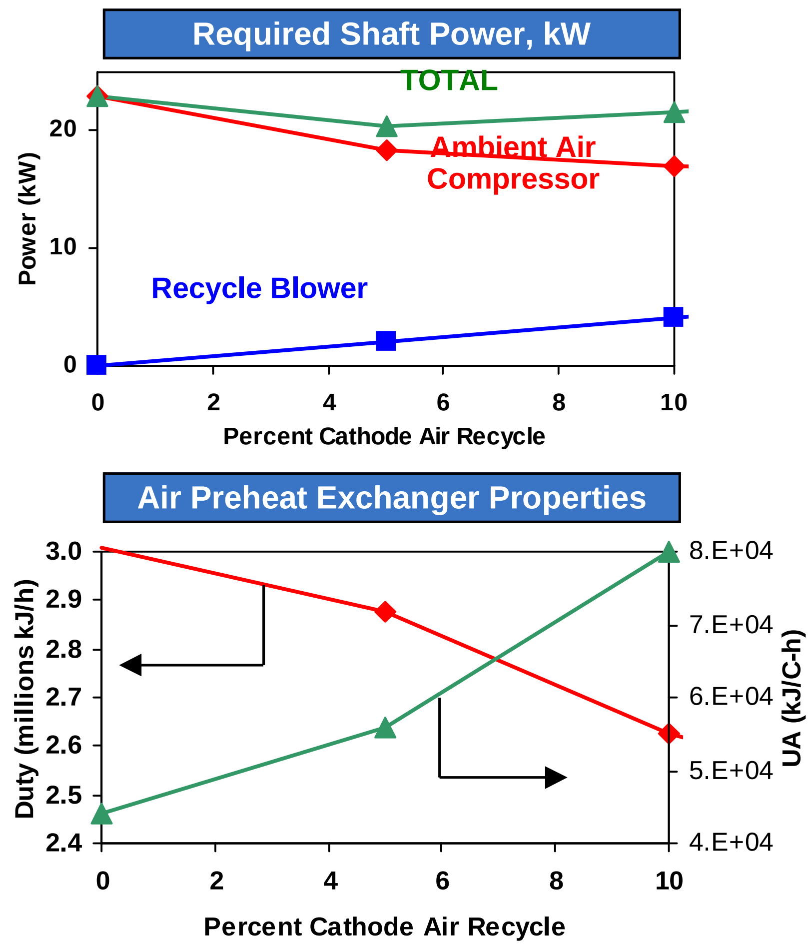
- 7.6 times excess cathode air is required for cooling the fuel cell (assuming maximum approach temperature of 150°C)
- A portion of this depleted air could be recycled, reducing fresh air requirements (and associated compression & preheating duty)
- An extra blower or air movement component would be required to recycle the depleted air
- However, the enthalpy transferred to reduce the fresh air preheat energy requirements may negatively impact the area of heat exchange required for air preheat, natural gas preheat and steam generation
- This analysis assumed that no fresh fuel was used in the SMR and that conversion in the SMR was unchanged

Degree of recycle is balanced by heat recuperation needed for air and fuel preheat.

Recycling depleted cathode air does not gain efficiency benefits in the scenario where exhaust gas is the sole fuel for the SMR and heat recuperation is used to preheat process streams.

- Recycling more than 10% of the depleted cathode air results in a temperature cross in the cathode air preheat exchanger
- Adding a recycle stream does not significantly effect the overall system efficiency in this scenario
  - The recycle stream requires a dedicated blower (adding to the parasitic load)
  - Even though the ambient air compressor is reduced, the total required shaft power remains approximately the same
  - Removing enthalpy from steam reformer fuel exhaust results in less energy available for heat recuperation for process stream preheat
- Increasing the recycle stream requires a bigger cathode air preheat exchanger
  - The exchanger area increases because the log mean temperature difference decreases

Recycle Effects on Cathode Air Preheater



Overall efficiency is ~50%; recycling 10% of the depleted cathode air does not impact the system efficiency strongly.

	Base Case	Cathode Recycle
Amount of Cathode Air Recycled	0	10%
Anode Fuel Utilization	85%	85%
Fuel Cell Efficiency[1]	47.1%	47.1%
Fuel Cell, Cell Voltage	0.7 V	0.7 V
SMR Effluent Temperature	800ºC	800ºC
Cathode Inlet Air Temperature	650ºC	650ºC
Required Cathode Excess Air[3]	7.7 times	7.5 times
Required Blower Pressure	1.17 bar	1.17 bar
Exhaust temperature	293ºC	296ºC
Parasitic Loads	**19.2 kW**	**25.8 kW**
Resultant Overall Efficiency[2]	**51.2%**	**50.0%**
Required Fuel Cell gross power rating, kW	**269.2**	**275.8 kW**

1. 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.
2. Overall system efficiency is defined as (fuel cell efficiency * reformer efficiency) - (energy required for parasitics)/(total energy input to system)
3. 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. Excess air is defined as (air required for cooling + air required for oxygen for anode reactions)/(air required for oxygen for anode reactions)

The selection of an appropriate steel is chosen primarily on its response to carburization and scaling.

- Carburization
  - The formation of metal carbides in a material as a result of exposure to a carbon containing atmosphere (such as natural gas and syngas)
  - As the steel absorbs carbon atoms, it becomes “heavier” and more brittle
  - Poor thermal expansion properties can lead to cracking
- Resistance to carburization generally centers around two mechanisms:
  - Establishment of an effective barrier on the surface of the materials that limits the ingress of carbon into the material. Chromium is commonly added to alloys resulting in the formation of a $Cr2O3$ barrier
  - Tying up carbon in the material using alloying elements which are strong carbide formers. The addition of nickel helps reduce the diffusion of carbon
- Scaling
  - The cracking and breaking off of the oxidized outer layer of the steel
  - Results in the formation of thin spots in a steel wall
  - The resulting debris will flow through downstream sections
  - Scaling becomes more severe as operating temperatures increase due to higher thermal stresses
  - Steels with good scaling resistance have the ability to keep the scale in one sheet

The general class of austenitic steels are most suitable for this application.

- Austenitic steels have elevated chromium levels and added nickel
- Characteristics:
  - Are not magnetic
  - Cannot be hardened by heat treatment but can be hardened by cold working
  - Have the best corrosion resistance
  - Can be easily welded
  - Have excellent cleanability and hygiene characteristics
  - Have exceptional resistance to both high and low temperature
- Common Uses:
  - Kitchen sinks
  - Architectural applications such as roofs and gutters, doors and windows, tubular frames
  - Food processing equipment
  - Restaurant food preparation areas
  - Chemical vessels
  - Ovens
  - Heat exchangers

There are a variety of different steel alloys that meet the performance requirements for the heat exchangers.

Grade	Ni (%)	Cr (%)	Si (%)	Other (%)	Maximum Intermittent Use Temperature (F)	Maximum Continuous Use Temperature (F)	Properties	Cost Ratio*
309	12	22	1	Mn:2	1800	2000		1.4
316L	14	18	1	C:0.03, Mn:2, Mb:3	1600	1700	More resistent to carbide precipitation than 316	1
321	9-12	17-19	1	Ti:0.4, C:0.08, Mn:2	1500	1650	Titanium stabilized for carburization resistence	1
347	9-13	17-19	1	Nb:0.8, C:0.08, Mn:2	1500	1650	Niobium stabilized for carburization resistence	1.25
RA330	35	19	1.25	C:0.05	2000	2200	Very high nickel content	3

*Cost ratio is based on the price of 11 gauge random cut sheet in 5000lb volumes from Rolled Alloys. All costs are relative to the price of 316L stainless. Base price of 316L stainless is $1.28/lb

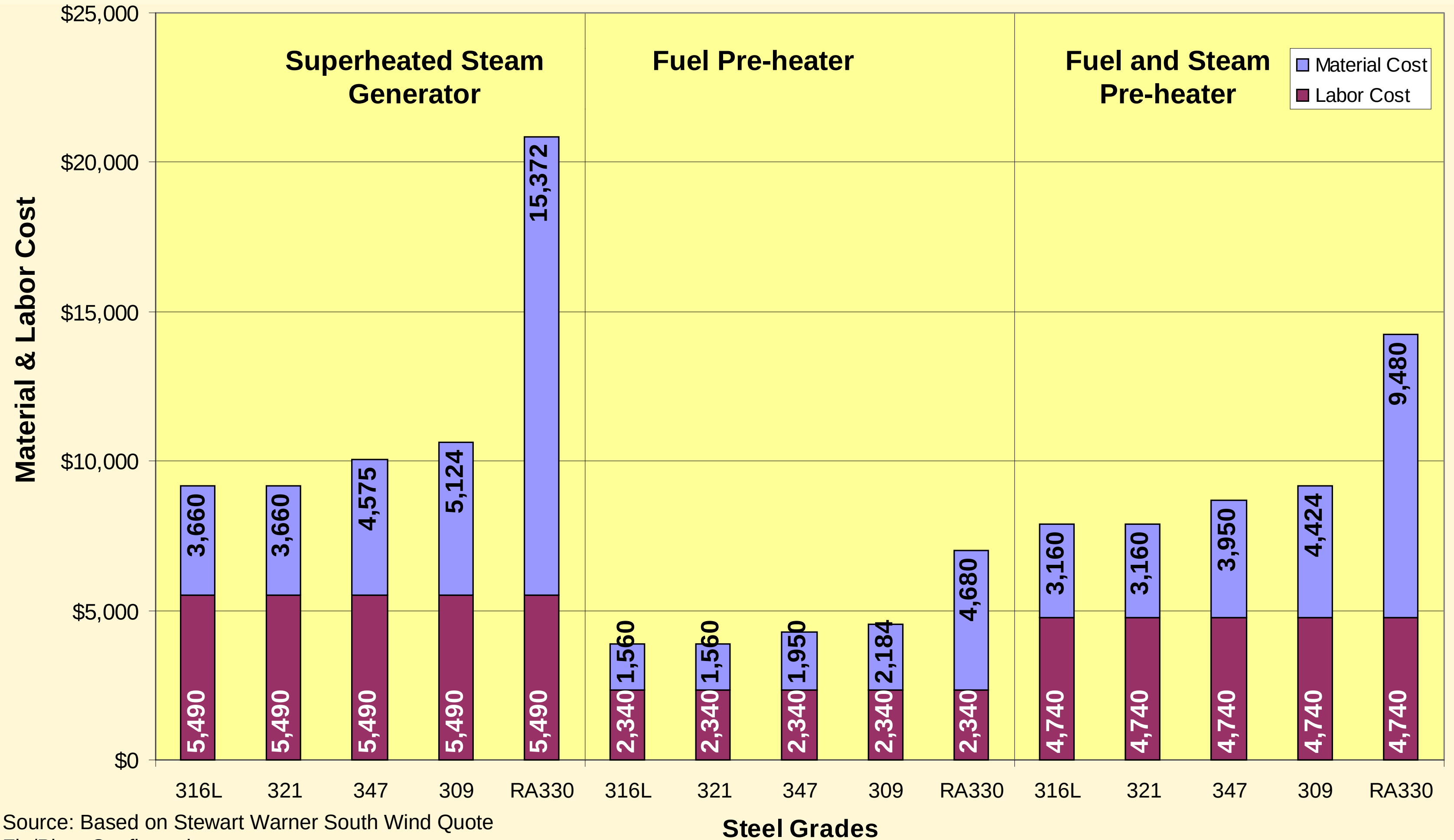
- 316L was used as the baseline because it is the least expensive steel that can be used for this application
- Under continuous use conditions, 316L is suitable for the Cathode Air Preheater
- The higher temperature heat exchangers should be constructed from a more temperature resistant steel such as 309
- A higher nickel content such as that in RA330 would provide greater longevity at the elevated temperatures, but is the most costly of the group

There is an overall heat loss of less than 4% of the total heat transferred, with significant reduction achieved through a nominal degree of insulation.

Compact Heat Exchanger Heat Loss to the Environment			
	Heat Loss	Heat Transferrred	
	KW	KW	% Heat Loss
Steam Generator			
Steam Collector	0.23		
Top End Plate	0.25		
Bottom End Plate	0.50		
Total	**0.97**	**107.70**	**0.90%**
Fuel Preheat	**0.06**	**9.85**	**0.59%**
Steam and Fuel Preheat 2			
Vertical Plates			
Inlet	0.31		
Outlet	0.44		
Horizontal Plates			
Upper	0.35		
Lower	0.70		
Total	**1.79**	**15.59**	**11.51%**
Cathode Air Preheat			
Vertical Plates	34.55		
Horizontal Plates			
Upper	0.10		
Lower	0.21		
Total	**34.86**	**700.56**	**4.98%**

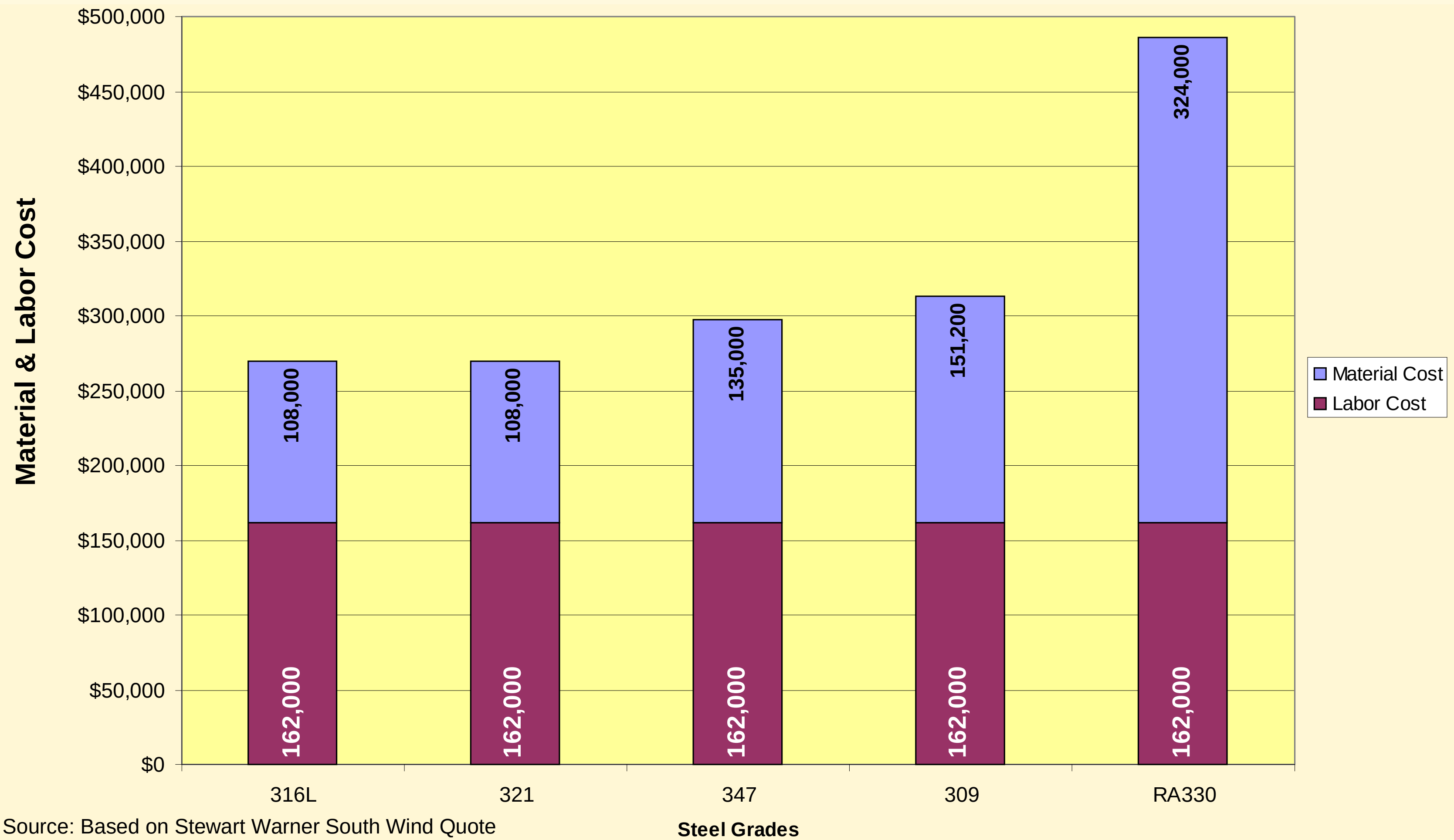
- No insulation used in calculations
- The heat loss calculations were made assuming the outside steel surface reaches the highest temperature flowing through the heat exchanger at steady state
- While the cathode air pre-heater has the greatest heat loss, its percent heat loss is relatively low due to its lower surface to volume ratio
- These losses can be reduced substantially by insulating the units

We have estimated materials costs for the production of 1 of each heat exchanger per year using upgraded steel alloys.



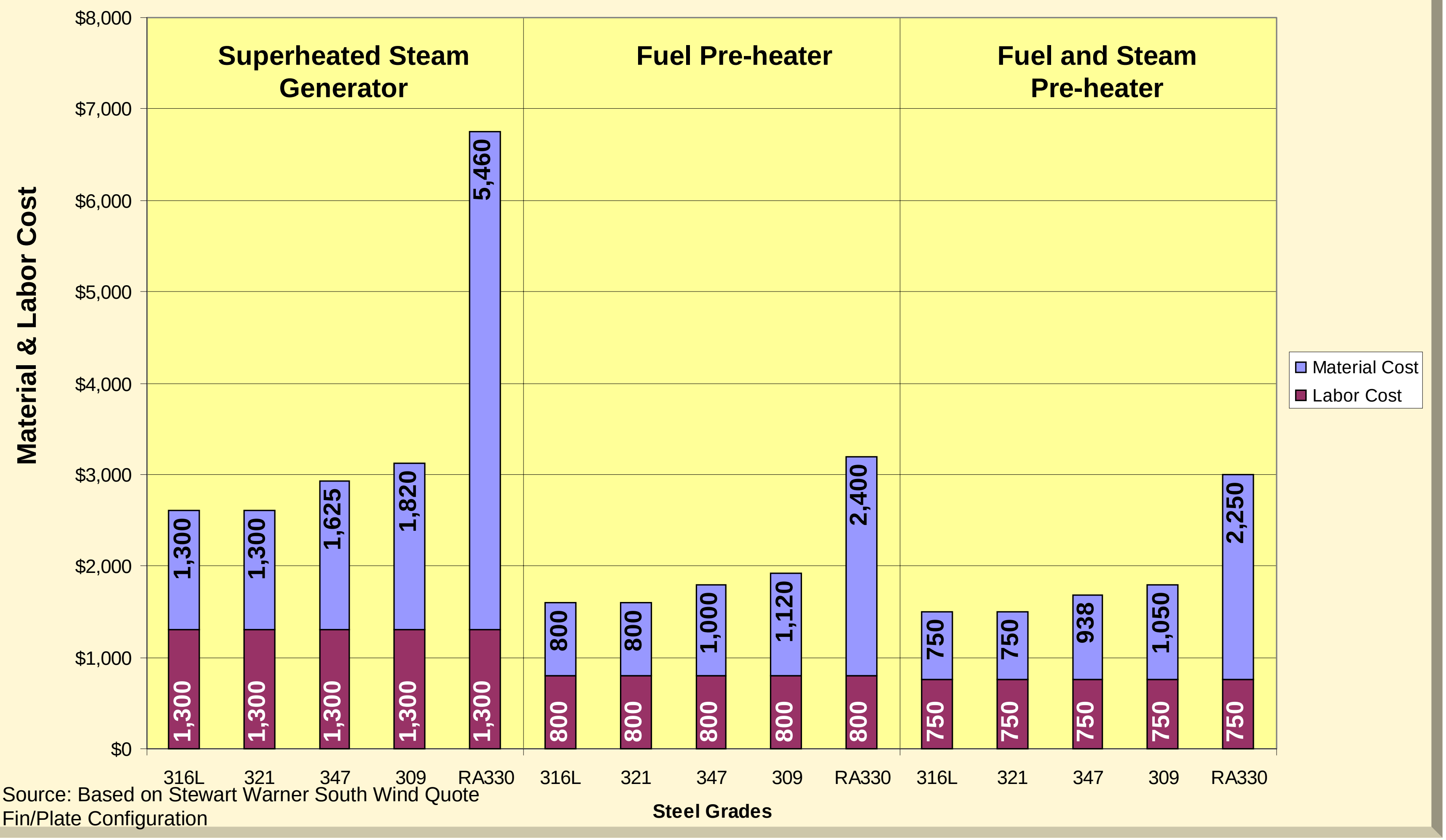
Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

We have estimated materials costs for 1 Cathode Air Pre-heater prototype using upgraded steel alloys.



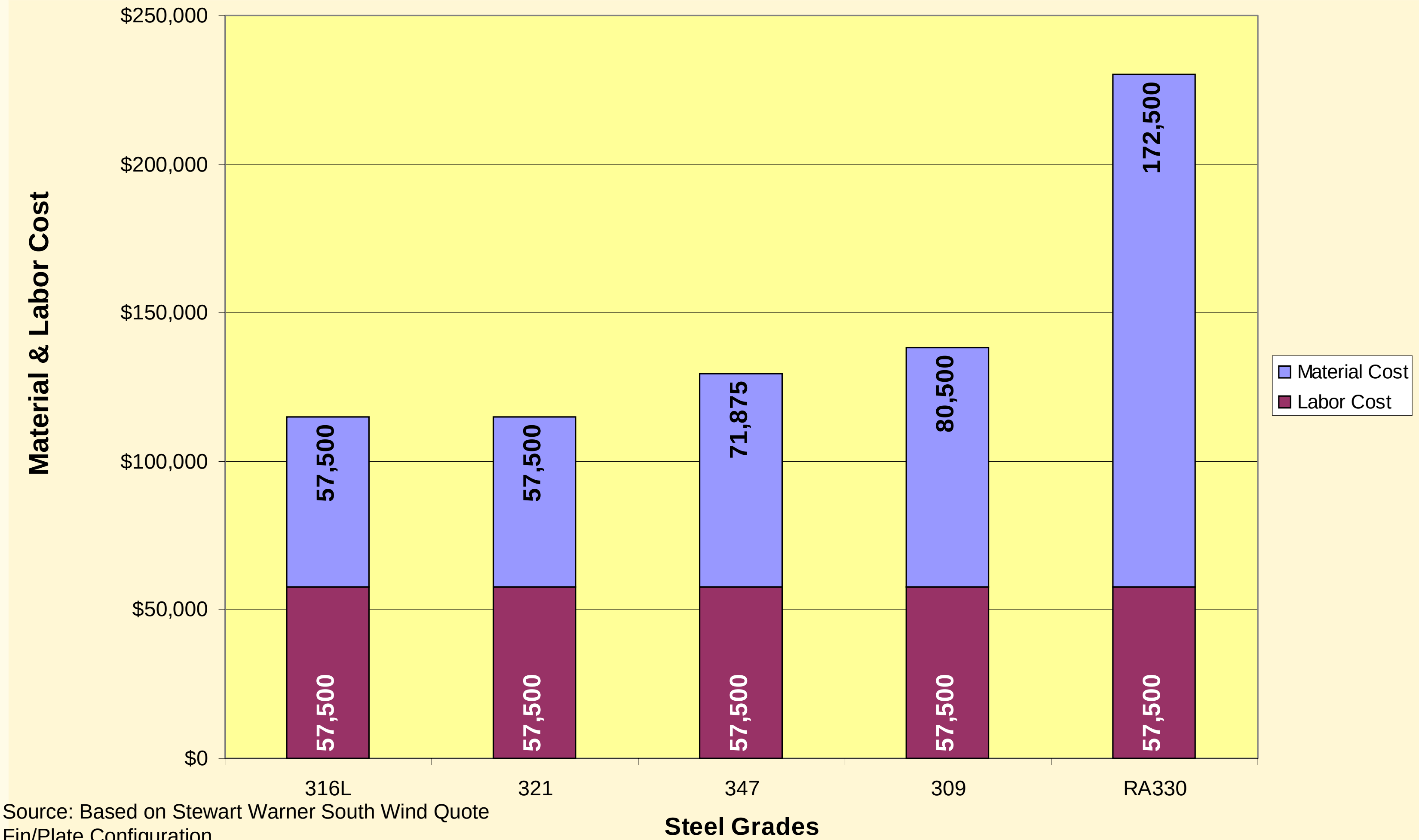
Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

We have estimated materials costs for the production of 100 of each heat exchanger per year using upgraded steel alloys.



Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

We have estimated materials costs for 100 Cathode Air Preheaters per year using upgraded steel alloys.



Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

Given the size benefit gained over shell and tube designs, we asked Stewart Warner to cost both prototype and larger production quantities.

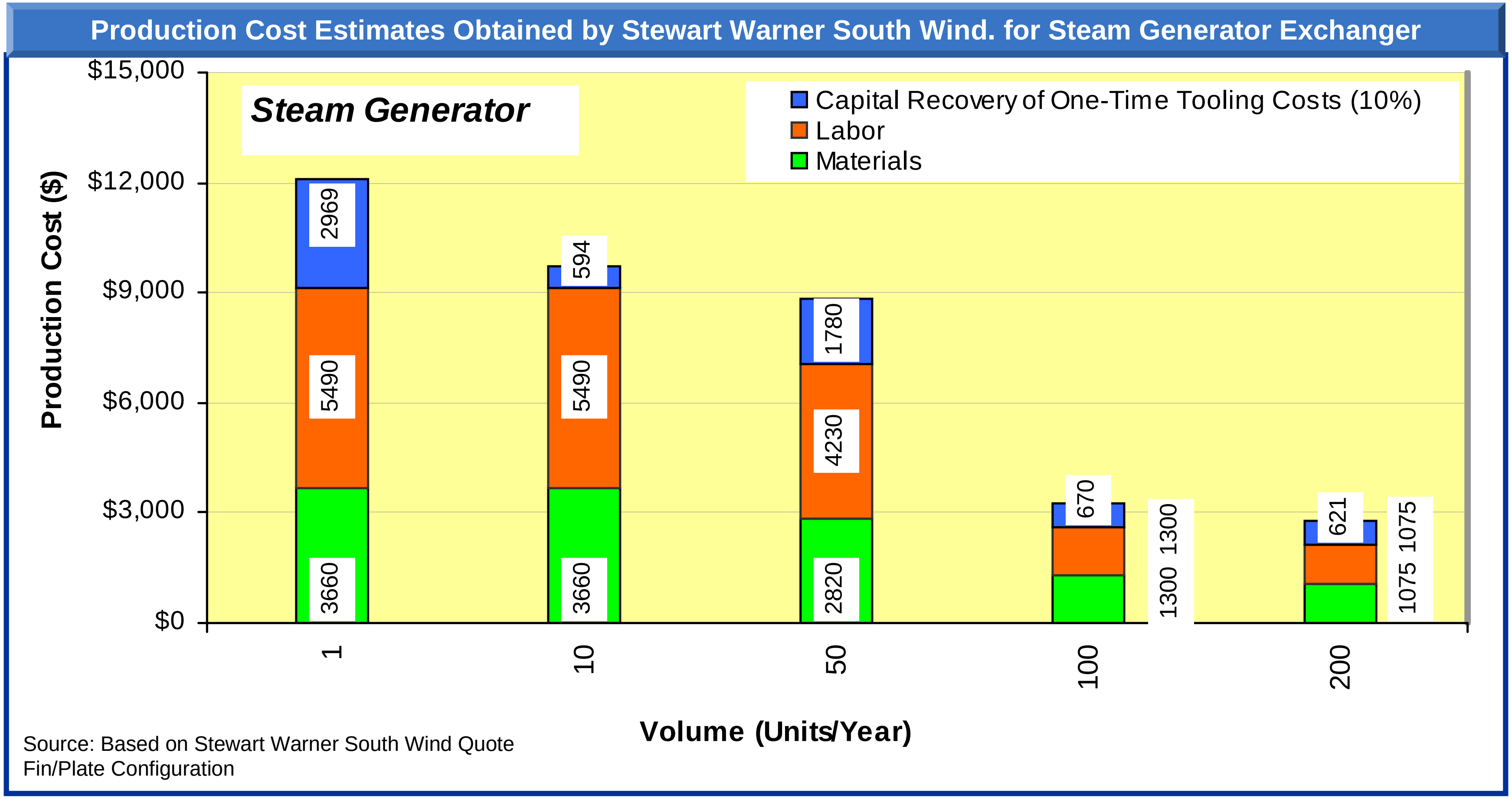
	One unit/yr		Ten units/yr		Fifty units/yr		100 units/yr		200 units/yr	
	Base	One Time Expense	Base	One Time Expense	Base	One Time Expense	Base	One Time Expense	Base	One Time Expense
Steam Generator	$9,150	$68,000	$9,150	$68,000	$7,050	$127,000	$2,600	$1,402,000	$2,150	$2,677,000
Fuel Preheat	$3,900		$3,900		$3,100		$1,600		$1,350	
Steam / Fuel Preheat	$7,900		$7,900		$5,300		$1,500		$1,250	
Cathode Air Preheat	$270,000	$130,000	$270,000	$130,000	$175,000	$1,780,000	$115,000	$3,755,000	$100,000	$4,955,000

* Steam generator, Fuel Preheat, and Steam/ Fuel Preheat share one time expense if heat exchangers are made by one manufacturer.

NOTES:
1. Compact plate/fin heat exchanger design
2. Pricing does not include fittings or insulation. Costs are based on quotes; no extrapolation in the data shown.
3. Base cost includes direct labor and materials using 316L materials
4. The split of material/labor was estimated by the manufacturer as 40/60 Material/Labor for 1 to 50 units per year; and 50/50 material/labor for over 100 units per year
5. The one time expense for the steam generator, fuel preheat and steam/fuel preheat exchangers is the one-time tooling capital investment in order to produce all three types of these heat exchangers
6. Large increments in one-time expenses represent capital investments required to reach production capacity.

Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

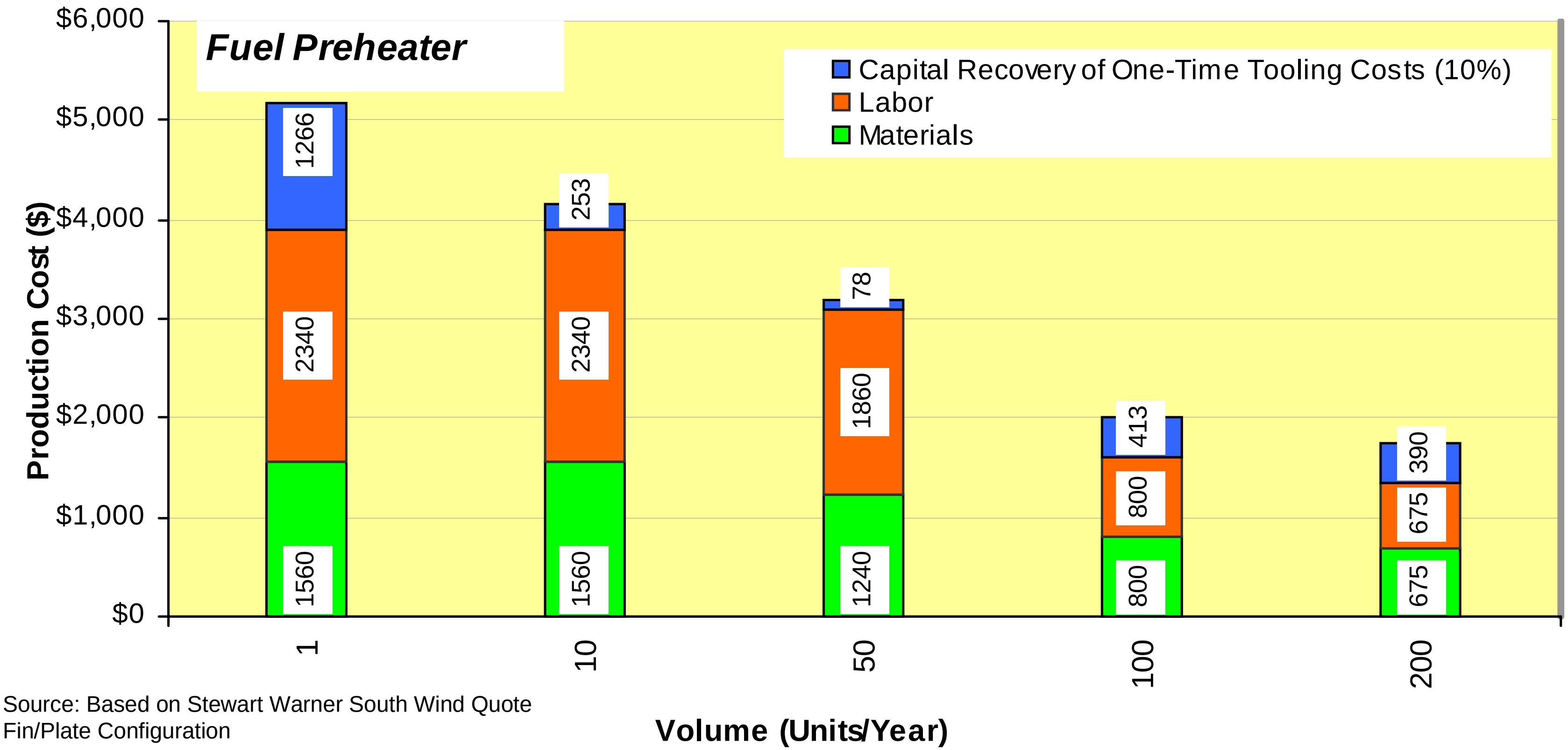
At moderate volume production (50 or more units/yr), the cost of the three smaller heat exchangers are each under $10k.



NOTES:
1. One time costs are divided among the heat exchangers proportional to base per part costs and are assumed to be recovered over a period of 10 years.

At moderate volume production (50 or more units/yr), the cost of the three smaller heat exchangers are each under $10k.

Cost Estimates Obtained by Stewart Warner South Wind. for Fuel Preheat Exchanger

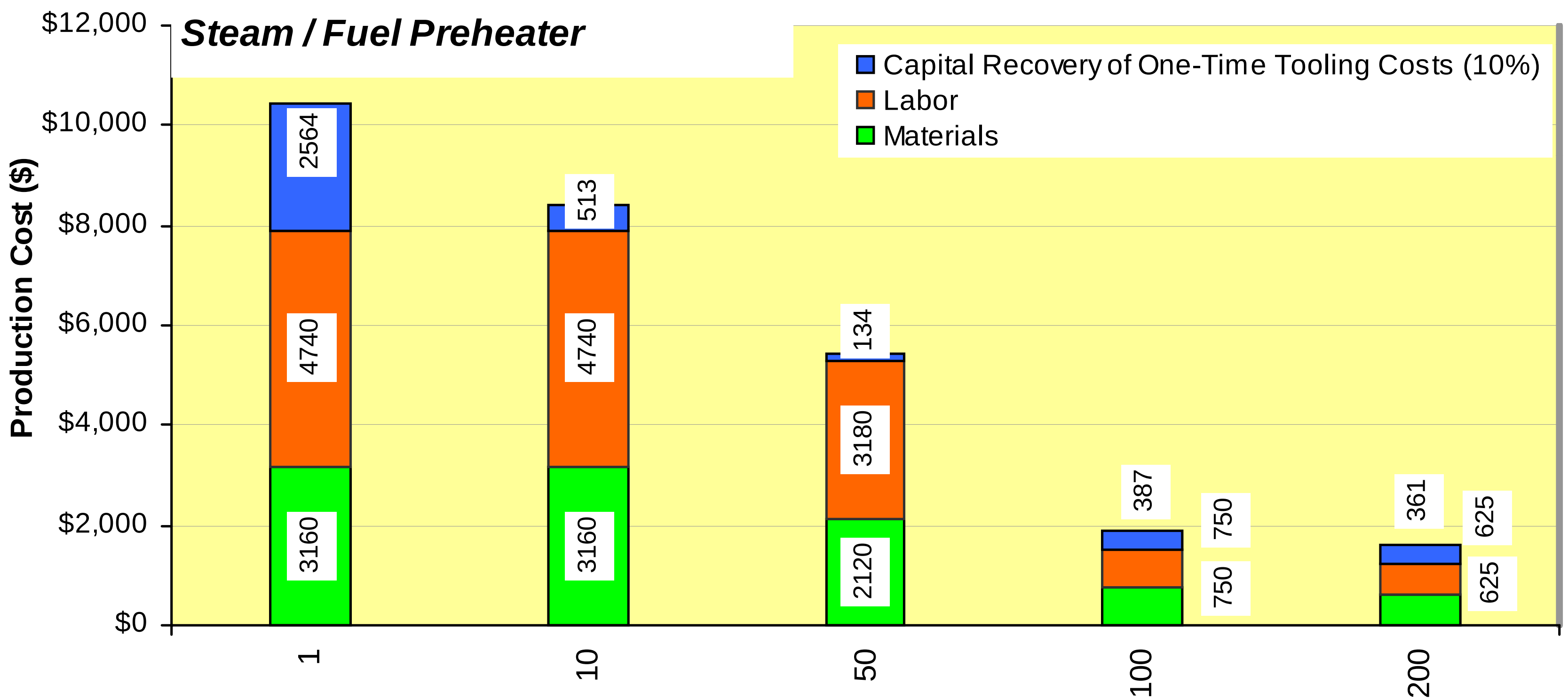


Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

NOTES:
1. One time costs are divided among the heat exchangers proportional to base per part costs and are assumed to be recovered over a period of 10 years.

At moderate volume production (50 or more units/yr), the cost of the three smaller heat exchangers are each under $10k.

Cost Estimates Obtained by Stewart Warner South Wind. for Steam/Fuel Preheat Exchanger



Source: Based on Stewart Warner South Wind Quote
Fin/Plate Configuration

NOTES:
1. One time costs are divided among the heat exchangers proportional to base per part costs and are assumed to be recovered over a period of 10 years.

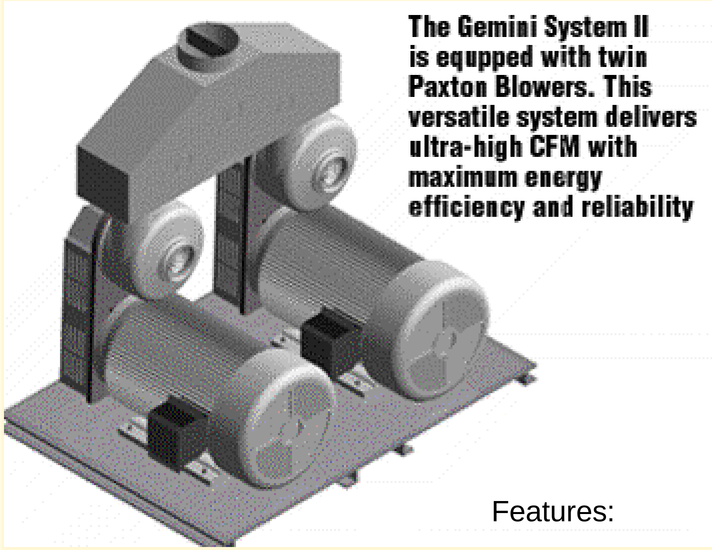
Compact heat exchangers photos

Close up of the plate and fin core

Full view of a compact heat exchanger

Source: Stewart-Warner Southwind Corporation

Centrifugal blowers are also made in twin single staged blower models.



Ultra-High Flow

Gemini, the Ultra-High Flow, compact Centrifugal Blower and Exhauster system from Paxton. Designed for air delivery of 2400 CFM and higher, pressures to 130" or vacuum to 100" H_20.

Gemini System II Series features an advanced Automatic Belt Tensioning system which eliminates belt surveillance, reduces maintenance and extends service life of belts and blowers. The Gemini System II provides excellent reliability combined with ease of service and high energy efficiency.

Features:

- Compact Design
- Energy Efficient
- Longer Life
- Oil-Free, Dry Air
- Air-Cooled Units to 120° F
- Water-Cooled Units to 325° F
- Available in 2 sizes: 30 HP & 40 HP
- Ideal for central vacuum or pressure systems and aeration
- Corrosion-Resistant Coatings Available
- Maintenance Free; For Continuous Duty
- Dynamically Balanced During Production
- Long-Life, High-Speed Micro-Groove Drive Belt and Pulley

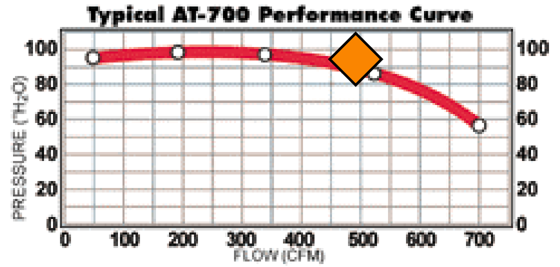
Specifications

Blower Height (in)	29.17
Manifold Height (in)	13.75
Total Height (in)	42.92
Width (in)	42
Depth (in)	36

Volume Costing		
1-10 Units	11-20 Units	21-50 Units
$ 14,925	$ 13,433	$ 11,940

*Quote received from Paxton Blower

Smaller Centrifugal blowers can be connected using a manifold.



Designed to operate most effectively up to 700 CFM. The third generation, high-efficiency impeller design is the key to Paxton's advanced line of centrifugal blowers. The efficient geometry and unique fabrication technique achieve very low drag combined with superior aerodynamics capability. All of the AT Line of high-performance blowers come equipped with field-proven PaxMATIC Automatic Belt Tensioning.

The third generation impellers dramatically reduce the blower / exhauster speeds as much as 20%, creating less internal heat, noise and vibration and using less power! All these benefits add up to trouble-free operation, providing more air flow at higher pressures and vacuums, at lower operating cost and longer life.

Available with water-cooled bearing housings for use in environments up to 325° F. ambient (higher for certain applications)

Features:

- Compact Design
- Economy + Performance
- Energy Efficient
- Quiet Operation
- Longer Life
- Oil-Free Operation
- Air-Cooled Units to 120° F
- Automatic Belt Tensioning (1 minute belt change, no tools required)
- Corrosion-Resistant Coatings Available
- Maintenance Free; For Continuous Duty
- Dynamically Balanced During Production
- Long-Life, High-Speed Micro-Groove Drive Belt and Pulley
- Water-Cooled Units to 325° F

	Volume Costing		
	1-10 Units	11-20 Units	21-50 Units
Individual	$ 3,747	$ 3,127	$ 2,779
4 Manifolded	$ 14,988	$ 12,508	$ 11,116

*Quote received from Paxton Blower

Total Height (in) without manifold	28
Width (in)	14
Depth (in)	21

Several blower arrangements were investigated.

- The blower requirements are to deliver 1950 CFM of cooling air at 2.5 psig
- Multistaged centrifugal blower is the most cost effective option
- Twin staged centrifugal blower is the most compact design
- Connecting several smaller multistaged blowers using a manifold was investigated to
  - Reduce cost through larger volumes (costing data shows a slight decrease in overall price at higher volumes)
  - Improve system reliability
    - If 1 of the 4 blowers fails, the system can still run at 80% power
    - When the blower is implemented as one large unit, the cost is lower, but if it fails the entire system must shut down while it is being repaired
    - Each blower manufacturer has stated that the blowers are designed to run continuously without failure
    - Military reliability data shows blowers have a low failure rate
      - As of 1995, 0 failures in over 1.2 million hours of use
      - This data is for a smaller blower, however, moving only 180 CFM
- Combining 4 smaller multistaged blowers adds a larger parasitic load than using one large unit
  - Each smaller blower requires 6.7 KW (33.5 KW combined)
  - The large blower requires 30 KW
- Air filters for each unit range between $500 and $600 depending on volume

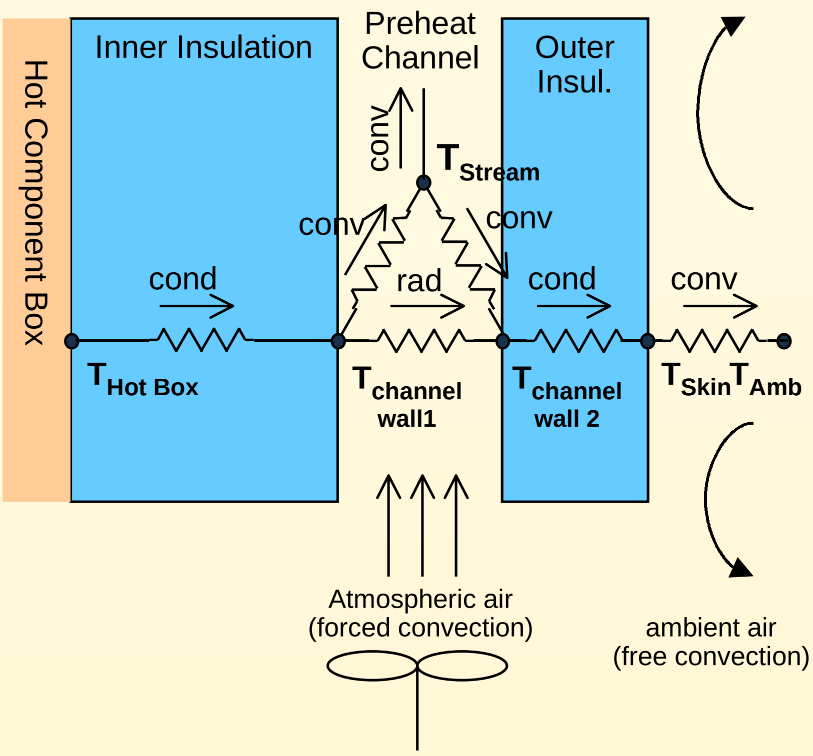
We modified our heat transfer model to include active cooling to reduce insulation volume and preheat the cathode process air.

Overview

Active Cooling Premise:

- Additional insulation volume reduction could be achieved with a dedicated blower/compressor, which also preheats the cathode air.
- The heat from the SOFC system box is taken away by both the air in the channel 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 cathode process air

Diagram of Equivalent Circuit



The thermal model uses seven heat transfer equations to simulate the heat loss from the SOFC system box to the process air and to the ambient air.

Thermal Model Description

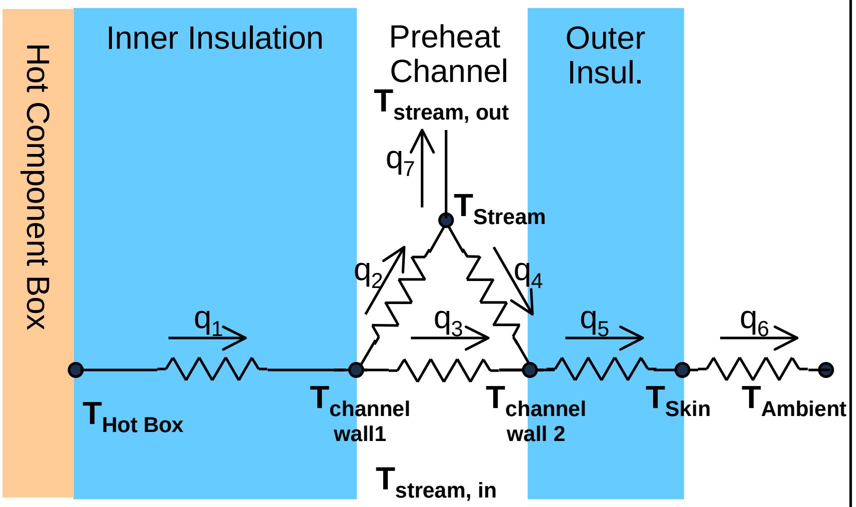
- The hot component box is assumed to be at a constant 550°C, with the heat loss dependent on what can be taken away with the process air and what is lost to the environment.
- The model varies the insulation thickness to minimize overall volume, while keeping the surface temperature less than 45°C.
- The flow rate of the cathode process air has a large effect on insulation volume. The more heat that can be removed with the process air, the less insulation that is needed.
- The thermal conductivity of the high temperature insulation was modeled to vary linearly with temperature while the low temperature insulation was set to a fixed value.
- Heat flow across each boundary is solved using a model of conduction through a flat plate. It is assumed that the bottom of the box does not require insulation.

We used an equivalent circuit to model the cooling channel.

Overview

- Key Inputs
  - Steady state one dimensional heat flow
  - High temperature aerogel for inner insulation and polyurethane foam for outer insulation
  - $T_{Hot\ Box}$ = Temperature of hot box wall (550°C)
  - $T_{channel\ wall\ 2}$ = Temperature of outer insulation (149°C maximum)
  - T_{skin} = Temperature of outer insulation wall (45°C)
  - $T_{ambient}$ = Temperature of ambient air (10°C)
  - $T_{stream,in}$ = Temperature of entering process air (10°C)
  - $T_{stream,out}$ = Temperature of exiting process air (210°C)
  - $V_{hot\ Box}$ = Volume of hot box
  - $e_1 = e_2$ = emissivity of channel walls (0.28)
  - Nu = Nusselt Number for flow in channel (8.23)
  - $h_{channel}$ = Convective heat transfer coefficient of air in channel (25 W/m^2K)
  - h_{skin} = Convective heat transfer coefficient of air surrounding outer wall; free convection (4.4 W/m^2K)[1].
- Key Outputs
  - $V_{inner\ Ins}$ = Volume of high temperature insulation
  - $V_{outer\ Ins}$ = Volume of low temperature insulation
  - $T_{channel\ wall1}$ = Temperature of channel inner wall
  - $T_{channel\ wall2}$ = Temperature of channel outer wall

Diagram of Equivalent Circuit



Heat Equations

- Convective heat transfer coefficients = h = (Nu * k)/D
- Heat flow, q (W)
  - $q_1 = kA_a(T_{Hot\ Box} - T_{channel\ wall\ 1})/L$ (conduction)
  - $q_2 = h_{channel}A_2(T_{channel\ wall\ 1} - T_{stream})$ (convection)
  - $q_3 = \sigma A_B(T^4_{ch\ wall\ 1} - T^4_{ch\ wall\ 2})/(1/\varepsilon_1 + 1/\varepsilon_2 - 1)$ (radiation)
  - $q_4 = h_{channel}A_3(T_{stream} - T_{channel\ wall\ 2})$ (convection)
  - $q_5 = kA_C(T_{channel\ wall\ 2} - T_{skin})/L$ (conduction)
  - $q_6 = h_{skin}A_4(T_{skin} - T_{ambient})$ (convection)
  - $q_7 = mc_{p,air}(T_{stream,\ in} - T_{stream,\ out})$ (convection)

Equations to be solved simultaneously

- Heat conducted through inner layer of insulation must equal heat lost through convection to channel air and by radiation to outer channel wall ($q_1 = q_2 + q_3$)
- Heat conducted through outer layer of insulation must equal heat gained through convection from channel air and by radiation from inner channel wall ($q_5 = q_3 + q_4$)
- Heat conducted through outer layer of insulation must equal heat lost through convection to ambient air ($q_5 = q_6$)
- Heat gained by channel air must equal heat gained through convection from inner channel wall and heat lost through convection to outer channel wall ($q_7 = q_2 + q_4$)