THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

By

Dr. William J. Sembler, Ph.D., P.E.

United States Merchant Marine Academy

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PRESENTATION

1. INTRODUCTION
2. TYPES OF FUEL CELLS
3. ADVANTAGES OF A SOLID-OXIDE FUEL CELL
4. SINGLE-CELL SOFC PARAMETRIC STUDY
5. MULTI-CELL SOFC ANALYSIS
6. FUEL CELL USE IN MARINE APPLICATIONS
7. SOFC HYBRID SYSTEMS TO GENERATE SHIPBOARD ELECTRICAL POWER
8. OVERALL CONCLUSIONS
9. QUESTIONS

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INTRODUCTION

WHAT IS A FUEL CELL?

- A DEVICE THAT CONVERTS CHEMICAL ENERGY INTO ELECTRICAL ENERGY

- DISCOVERED BY WILLIAM GROVE IN 1839

- BASIC FUEL CELL CONSISTS OF TWO ELECTRODES SEPARATED BY AN IONIC-CONDUCTING ELECTROLYTE

- IONS FORMED AT ONE ELECTRODE ARE CONDUCTED THROUGH THE ELECTROLYTE

- LIBERATED ELECTRONS PASS THROUGH AN EXTERNAL CONDUCTOR CREATING A DIRECT CURRENT

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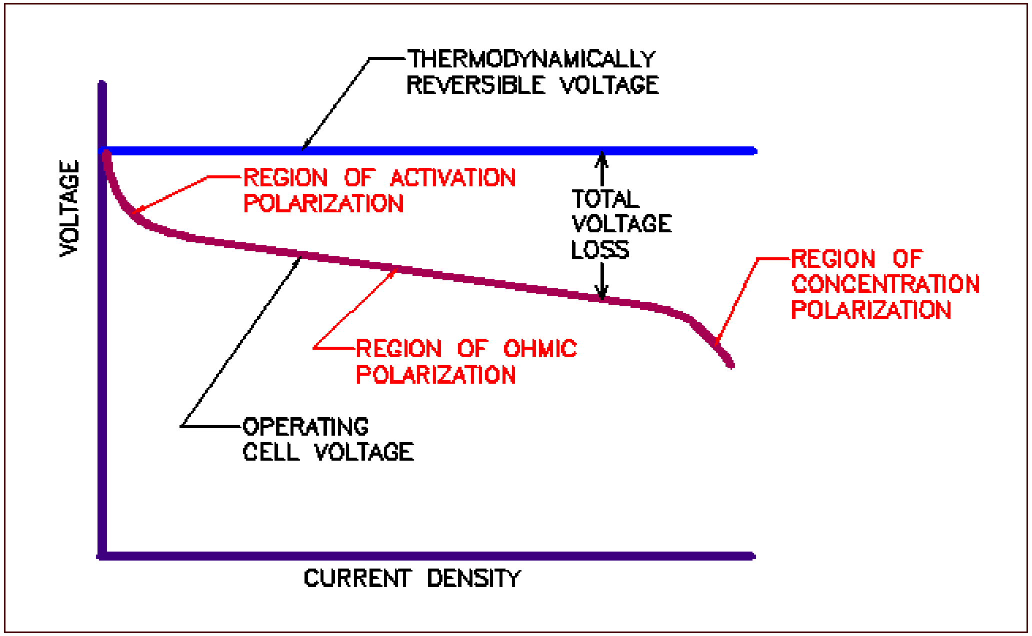
FUEL-CELL VOLTAGE



Fuel Cell Voltage vs. Current Density

Thermodynamically reversible (Nernst) voltage generated by a fuel cell

$$E = \frac{-\Delta \bar{g}_f}{n_{fuel}\,(F)}$$

F = Faraday constant, 9.6485 E4 C/mol of electrons

Maximum current produced by a fuel cell with 100% utilization of a fuel and sufficient oxidizer:

$$i_{max} = n_{fuel}\,(F)\,\dot{N}_{fuel}\left(1000\,\frac{mol}{kmol}\right)$$

Voltage Losses in a Fuel Cell

➢ **Activation Losses.** Energy required to drive electrochemical reactions; reduced as the rates of the electrochemical reactions within a fuel cell increase.

➢**Fuel Crossover and Internal Currents.**

- Internal current conducted through electrolyte.
- Fuel supplied to a fuel cell that diffuses and migrates through the electrolyte.

➢ **Ohmic Losses.** Resistance to the transport of electrons in the electrodes, interconnectors, and electrical circuit (including contact resistance) and to the conduction of ions through the electrolyte.

➢ **Concentration or Mass Transport Loss.** Due to a reduction in the concentrations of the reactants and an increase in the concentrations of the products at the electrode-electrolyte interfaces relative to the bulk concentrations.

WHY THE INTEREST IN FUEL CELLS?

- WHEN SUPPLIED WITH HYDROGEN AND OXYGEN, PRODUCTS ARE ELECTRICITY, WATER AND HEAT – NO POLLUTANTS ARE PRODUCED.

- CAN BE MORE EFFICIENT THAN A TYPICAL DIESEL-ENGINE – EMISSIONS WITH FUELS OTHER THAN HYDROGEN WILL TYPICALLY BE LESS THAN THOSE PRODUCED BY A COMPARABLY SIZED DIESEL ENGINE.

- HEAT GENERATED CAN BE UTILIZED IN OTHER SYSTEMS OR COMPONENTS.

TYPES OF FUEL CELLS

Alkaline Fuel Cell (AFC): One of the earliest types of cells used. Electrodes are separated by a liquid electrolyte consisting of a solution of potassium hydroxide in water. Some electrodes are made from carbon-supported catalysts that are mixed with poly-tetrafluoroethylene (PTFE) and rolled onto a nickel mesh. Alternatively, porous Raney nickel and silver have been used for anodes and cathodes, respectively. AFCs were used in the U.S. Apollo Space Program in the late 1960s and 1970s and are currently used in the Space Shuttle

- **Proton Exchange Membrane Fuel Cell (PEMFC):** Contains two porous carbon electrodes separated by a thin solid polymer electrolyte that is coated on both sides with a platinum-based catalyst. Dupont Nafion® is a commonly used electrolyte material. PEMFCs were used in the U.S. Gemini Space Program in the mid 1960s.

- **Phosphoric Acid Fuel Cell (PAFC):** The electrolyte consists of phosphoric acid that is contained within the pores of a matrix of silicon carbide held together with a small amount of PTFE. Electrodes are typically constructed from porous graphite that is coated with a platinum (Pt) catalyst.

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TYPES OF FUEL CELLS (contd.)

- **Molten Carbonate Fuel Cell (MCFC):** The electrolyte consists of a molten mixture of lithium and either potassium or sodium carbonates suspended in a porous chemically inert ceramic lithium-oxide matrix. Commonly used electrode materials include porous sintered nickel-chromium/nickel-aluminum alloy for anodes and nickel oxide for cathodes.

- **Solid Oxide Fuel Cell (SOFC):** A solid ceramic electrolyte is located between two porous electrodes. Zirconia stabilized with a small percentage of yttria (Y2O3), referred to as YSZ, is a common electrolyte material. A typical SOFC anode is made from a cermet consisting of nickel in a YSZ skeleton, and a common cathode material is strontium-doped lanthanum manganite (LSM).

FUEL-CELL COMPARISON

TYPE	AFC	PEMFC	PAFC	MCFC	SOFC
Reforming	External only			Internal and External	
Fuels	H_2			H_2 & CO	
Oxidizers	O_2			O_2 & CO_2	O_2
Mobile Ion	OH^-	H^+		CO_3^{2-}	O^{2-}
Anode Exhaust	Excess Fuel & H_2O	Excess Fuel		Excess Fuel, H_2O (if H_2 in fuel), & CO_2	Excess Fuel, H_2O (if H_2 in fuel), & CO_2 (if CO in fuel)
Cathode Exhaust[A]	Excess Oxidizer	Excess Oxidizer & H_2O		Excess Oxidizer	
Typical Operating Temperature	50 to 200 C	30 to 100 C	205 to 220 C	650 C	800 to 1000 C[B]
Advantages	Lower activaltion loss at cathode than with acid electrolyte	Suitable for portable applications	Water management simplified with 100% acid electrolyte	250+ kW units commercially available	High temperatures reduce ohmic losses
				CO can be used as a fuel	
	Low cost electrolyte	solid electrolyte	Low-cost electrolyte	High waste heat for cogeneration	Highest waste heat available
		Good start-stop capability	High Reliability	Non-precious-metal catalysts may be used	
	Non-precious-metal catalysts may be used	High power density	Mature technology	Less thermal material degradation than SOFC	Planar can have high power densities
					Solid electrolyte

FUEL-CELL COMPARISON (CONTD.)

<table>
<tr><th>TYPE</th><th>AFC</th><th>PEMFC</th><th>PAFC</th><th>MCFC</th><th>SOFC</th></tr>
<tr><td rowspan="5">Disadvantages</td><td>CO_2 reacts with electrolyte</td><td colspan="2">Requires expensive precous-metal catalyst</td><td>Corrosive molten electrolyte</td><td>Least mature type</td></tr>
<tr><td>Electrolyte must be periodicaly replenished to makeup for evaporation</td><td>Water must be closely managed to prevent flooding electrodes</td><td>Electrolyte is corrosive & must be periodically replenished to makeup for evaporation</td><td>Electrolyte must be heated above carbonate melting point at startup
Stresses from freeze-thaw cycle of electrolyte during startup & shutdown</td><td>Heating required at startup
Extended startup time to limit temperature gradients
High temperatures can lead to material degradation</td></tr>
<tr><td rowspan="3">Water must be removed form anode to prevent electrolyte dilution</td><td>Bipolar plaes separating cells in a stack are costly</td><td>Stack cooling required</td><td>CO_2 must often be recycled from anode to cathode</td><td>Planar can be limited in size and difficult to seal</td></tr>
<tr><td colspan="2">CO can poisen catalyst in anode</td><td colspan="2">Materials can be relatively expensive</td></tr>
<tr><td colspan="4">Poor tolerance to sulfur</td></tr>
</table>

[A] Cathode exhaust also includes nitrogen and other non-O_2 components contained in any air supplied to the cathode.

[B] Intermediate-temperature SOFCs with operating temperatures from 873 K to 1073 K are also being developed

ADVANTAGES OF SOLID-OXIDE FUEL CELLS

- SOFCS HAVE THE HIGHEST OPERATING TEMPERATURES – GREATEST AMOUNT OF WASTE HEAT.
- STEAM GENERATED IN ANODE CAN BE UTILIZED FOR INTERNAL FUEL REFORMING.
- SOLID ELECTROLYTE – ELIMINATES NEED TO MONITOR ELECTROLYTE CHEMISTRY, WILL NOT BE AFFECTED BY VESSEL MOTION.
- CARBON MONOXIDE (CO) CAN BE UTILIZED AS A FUEL – WILL NOT POISON THE CELL.
- HIGH SOFC OPERATING TEMPERATURES – REDUCES IONIC RESISTANCE IN ELECTROLYTE AND ELECTRONIC RESISTANCE IN THE ELECTRODES; PRECIOUS-METAL CATALYSTS NOT REQUIRED.

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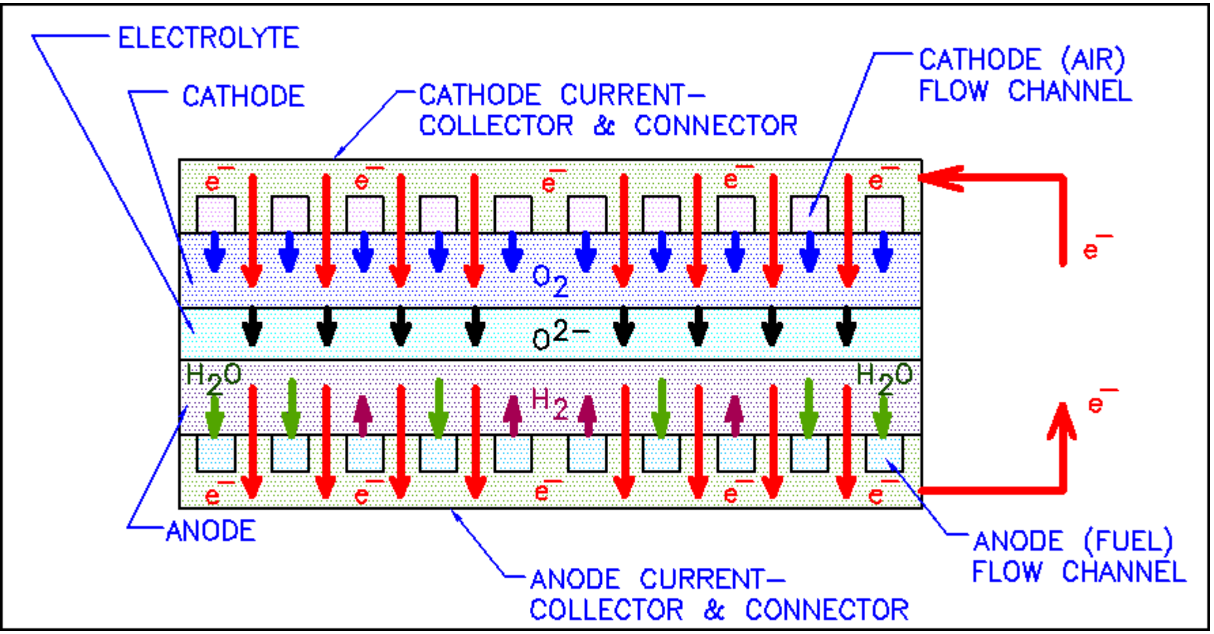
PLANAR SOLID-OXIDE FUEL CELL



Planar Solid-Oxide Fuel Cell Schematic

Electrochemical reactions in an SOFC supplied with hydrogen (H_2) and/or carbon monoxide (CO) as fuel and oxygen (O_2) as an oxidizer:

Cathode: $O_2 + 4\,e^- \rightarrow 2\,O^{2-}$

Anode: $2\,H_2 + 2\,O^{2-} \rightarrow 2\,H_2O + 4\,e^-$

$2\,CO + 2\,O^{2-} \rightarrow 2\,CO_2 + 4\,e^-$

- ➢ Negative oxygen ions from air supplied to the cathode are formed at the cathode-electrolyte interface.
- ➢ These oxygen ions are conducted through the electrolyte.
- ➢ These ions combine with hydrogen molecules (H_2) at the anode-electrolyte interface and form water (H_2O).
- ➢ Electrons separated from the oxygen ions are conducted through an external electrical circuit that joins the anode to the cathode creating direct current.
- ➢ When the electrons return to the cathode, they combine with the incoming oxygen to form new oxygen ions, and the aforementioned process is repeated.

SINGLE-CELL SOFC PARAMETRIC STUDY USING CFD

- OBJECTIVE
- THERMAL BOUNDARY CONDITIONS
- FUEL & AIR TEMPERATURES, FLOW RATES AND PRESSURES
- FUEL & AIR FLOW ORIENTATION
- FLOW-CHANNEL DIMENSIONS
- OPTIMUM CELL CONFIGURATION
- CONCLUSIONS OF PARAMETRIC STUDY

WHAT IS THE OBJECTIVE OF THIS PARAMETRIC STUDY?

- **To determine the effects of changing various parameters on the performance of a Solid-Oxide Fuel Cell (SOFC) CFD model.**
- **To verify that the effects of these changes predicted by the CFD analyses were consistent with fuel-cell theory.**
- **To use the CFD results to develop an optimized single-cell SOFC.**

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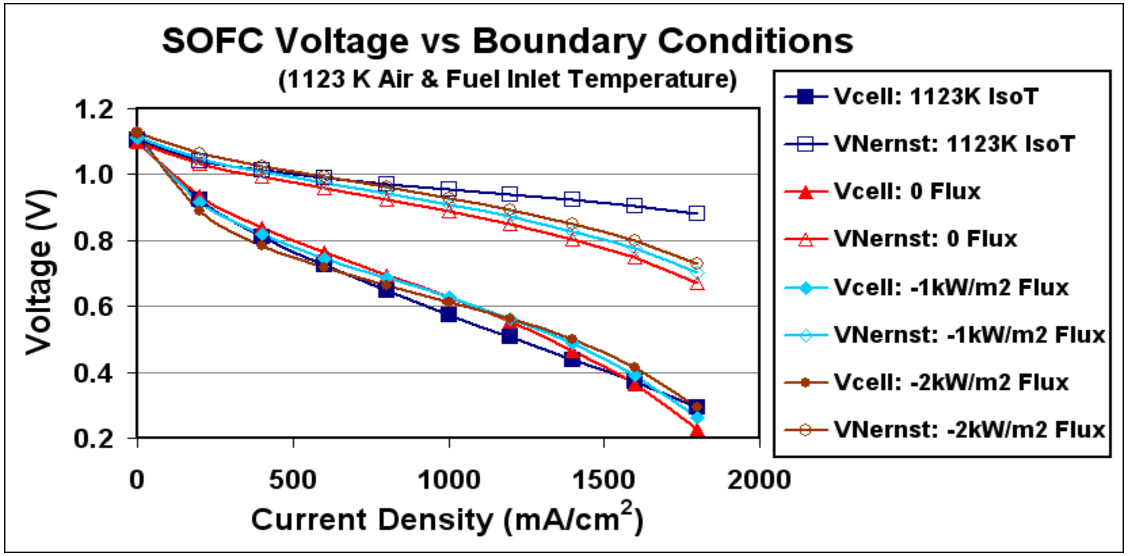
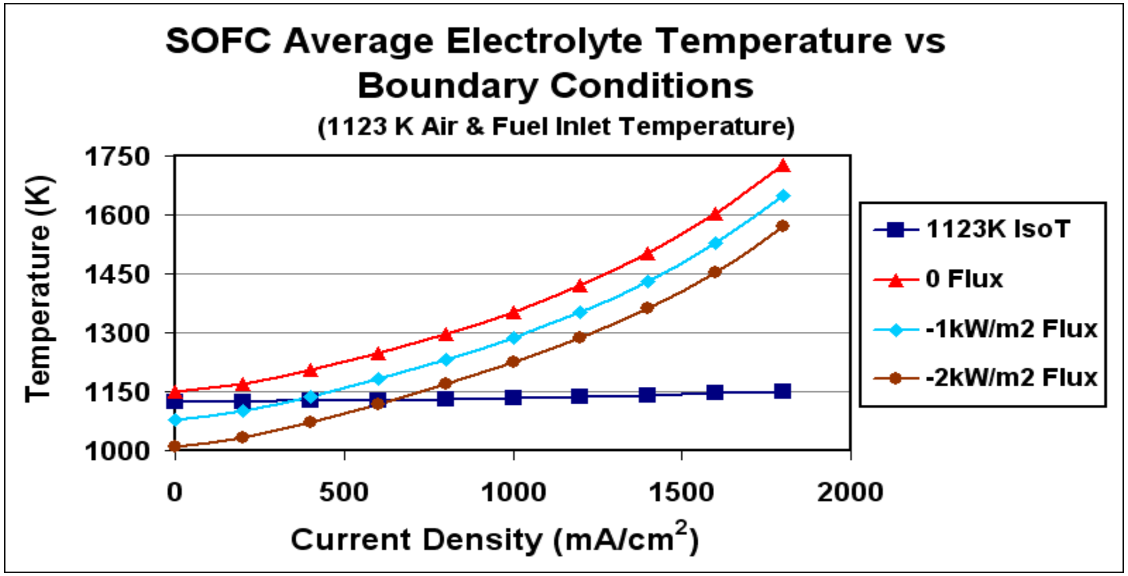
Thermal Boundary Conditions


SOFC Voltage vs Boundary Conditions

(1123 K Air & Fuel Inlet Temperature)


SOFC Average Electrolyte Temperature vs Boundary Conditions

(1123 K Air & Fuel Inlet Temperature)

- Four Boundary Conditions Analyzed: **0, – 1 kW/m^2, – 2 kW/m^2 & 1123 K**

- Average electrolyte temperatures increased with current density.

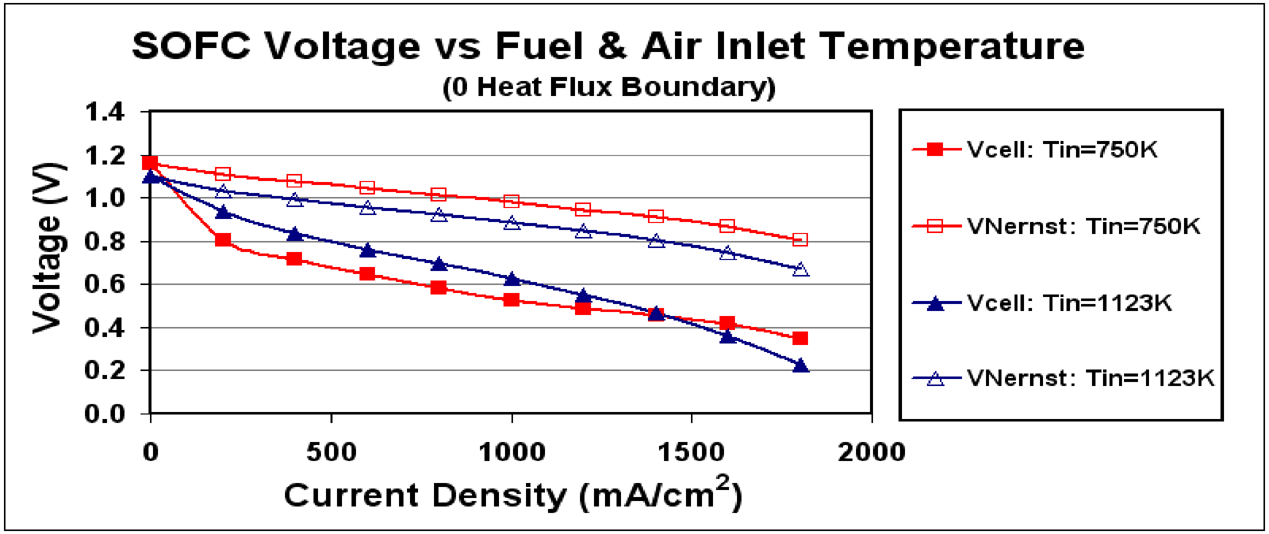
- Operation with adiabatic boundaries resulted in higher average electrolyte temperatures.

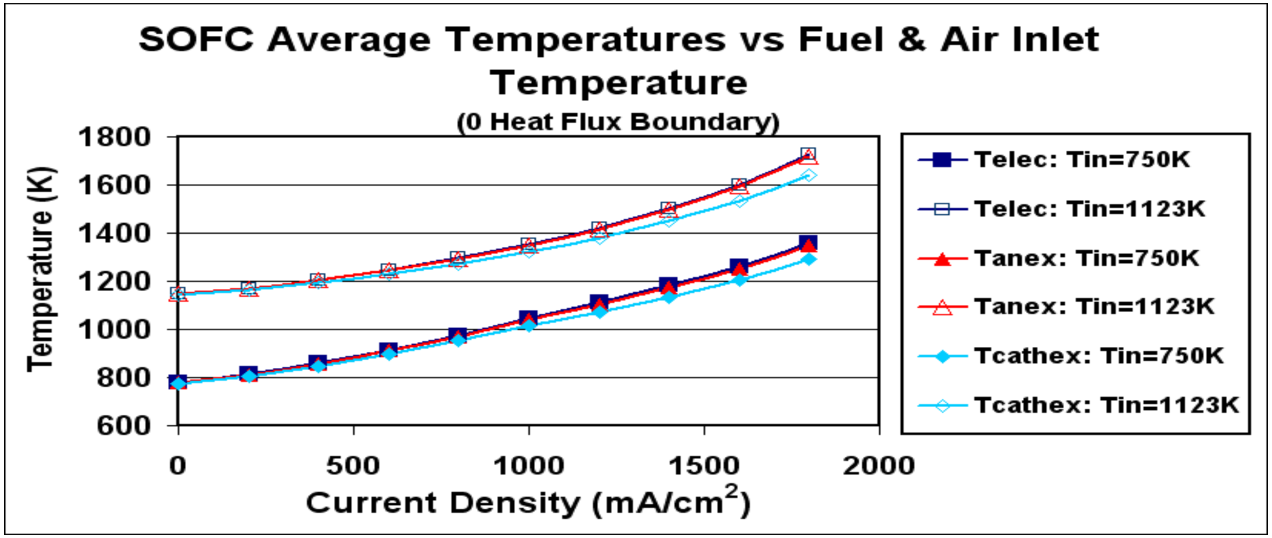
- The thermodynamically reversible or Nernst voltage was typically reduced as the temperature increased.

- Due to a reduction in resistance and Ohmic losses and often in activation losses at higher temperatures, the actual voltage produced by an SOFC generally increases with operating temperature.

- Because of this effect on cell voltage and because the utilization of waste heat is often critical to the operation of a hybrid system, with its higher operating temperatures, the adiabatic boundary condition was considered to be the preferred boundary condition of those evaluated .

FUEL & AIR INLET TEMPERATURES



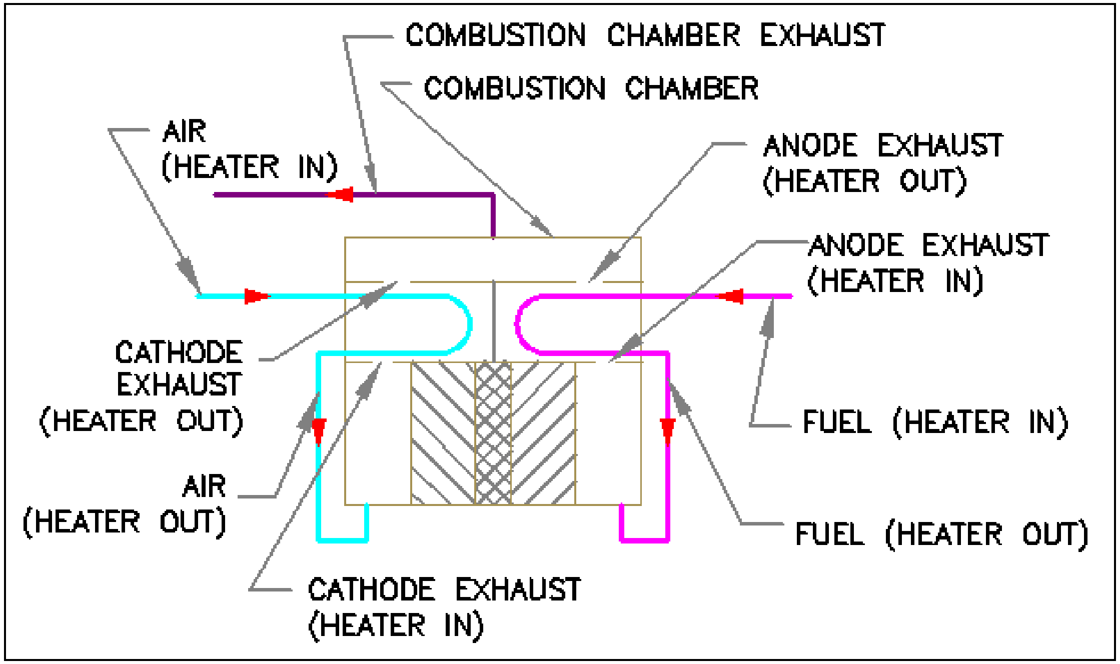


- Two Inlet temperatures analyzed: **1123 K & 750 K.**

- Higher fuel and air inlet temperatures resulted in higher average electrolyte temperatures.

- This reduced the Nernst voltage but increased the cell voltage produced when the current density was less than 1400 mA/cm^2.

Fuel & Air Heaters



SOFC with Air and Fuel Heaters

➢ If the fuel and air being supplied to an SOFC are to be heated by the cell's anode-exhaust and cathode-exhaust gas streams, <u>the temperatures of the fuel and air entering the fuel cell will be limited by</u>

- <u>The exhaust-gas temperatures</u>
- <u>The heat transfer achievable in the fuel and air heat exchangers</u>.

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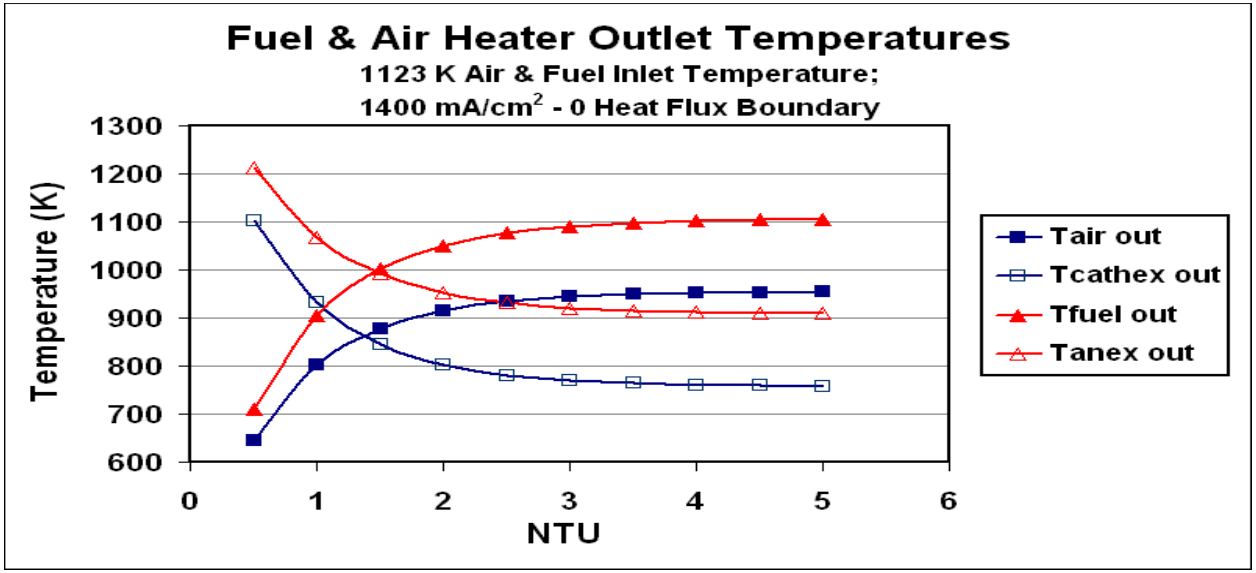
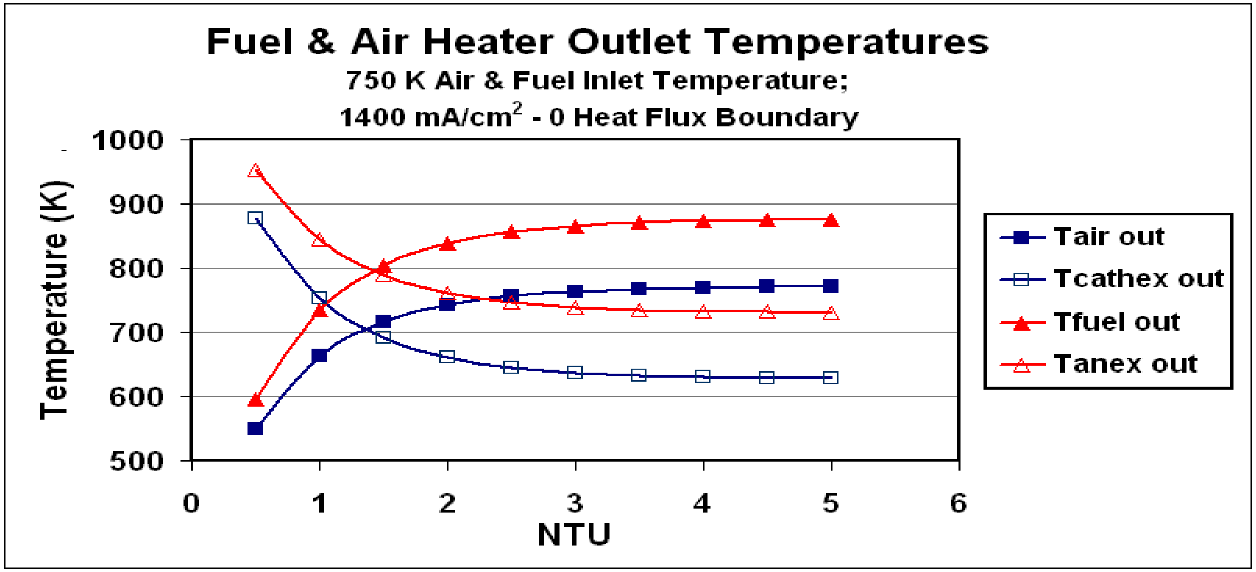
FUEL & AIR HEATERS



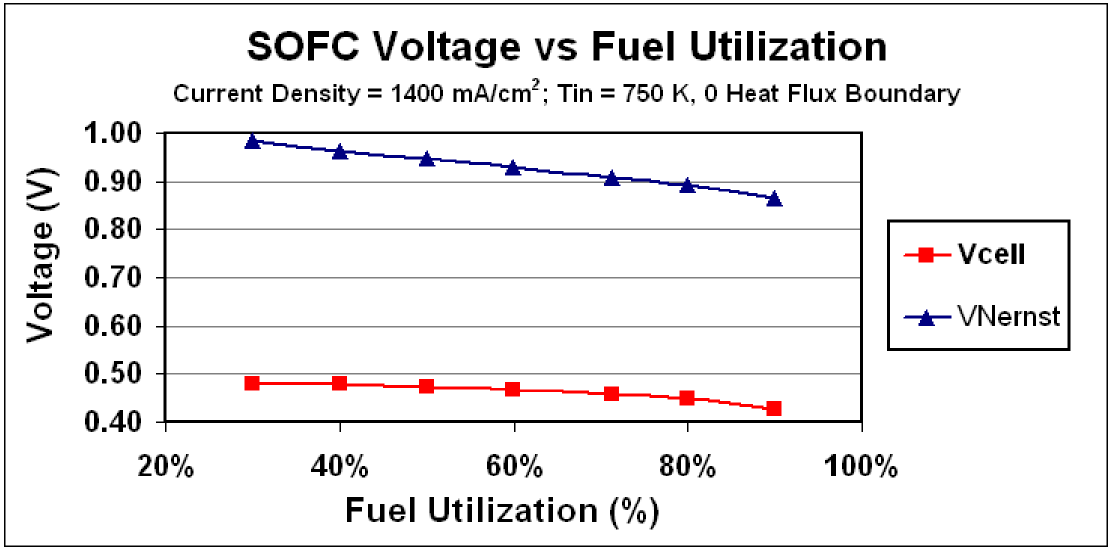


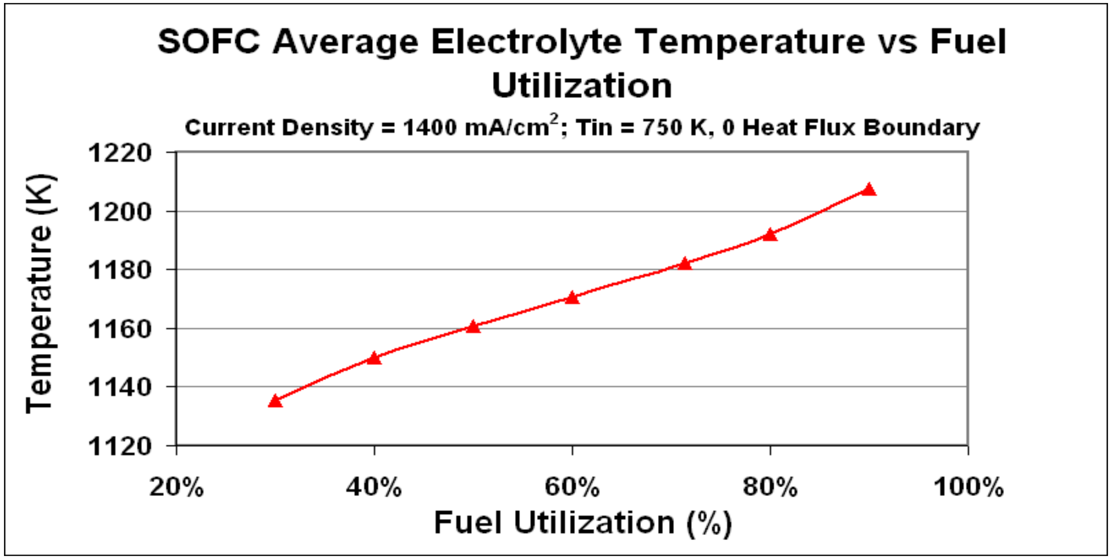
- The heat transferred from the SOFC exhaust gas in the air and fuel heaters was <u>not sufficient to heat the fuel or the air to the desired 1123 K</u>.

- <u>If the air and fuel temperatures at the inlet to the SOFC were reduced to the values at the air- and fuel-heater outlets</u>, the SOFC's exhaust-gas temperatures and the air and fuel heater-outlet temperatures would be reduced, which would <u>reduce the SOFC exhaust-gas temperatures to even lower values.</u>

- When air and fuel were both supplied to the SOFC at a temperature of <u>750 K</u>, the anode-exhaust gas <u>was hot enough to heat the incoming air and fuel to 750 K.</u>

FUEL FLOW RATE





- The **fuel utilization factor**, U, is the ratio of the fuel (hydrogen) mass flow rate required divided by the fuel mass flow rate supplied.
- **U** was varied from **30% to 90%**
- The increased mass flow rate of fuel associated with a reduced fuel utilization factor had a cooling effect on the cell and resulted in a reduced electrolyte temperature.
- This reduction in temperature resulted in an increase in the Nernst voltage,
- A reduction in fuel utilization also increases the reactant concentration at the anode-electrolyte interface, which reduces concentration losses and helps to increase cell voltage.
- Due to an increase in the Ohmic losses and, to a lesser extent, in the activation losses with the reduction in temperature, the cell voltage did not rises as steeply as the Nernst voltage when U was reduced, and it eventually leveled off.

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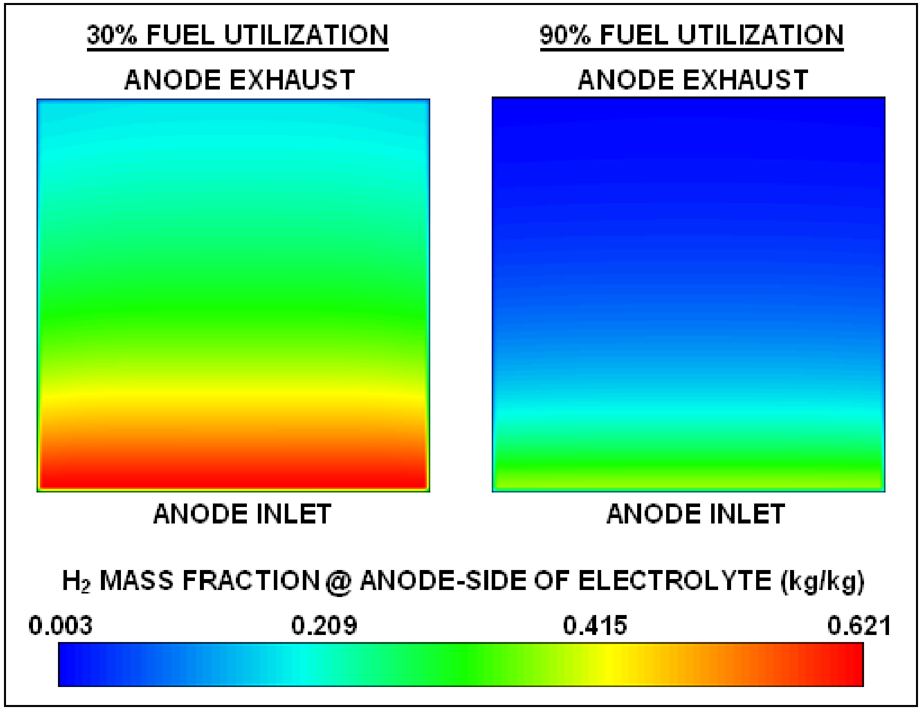
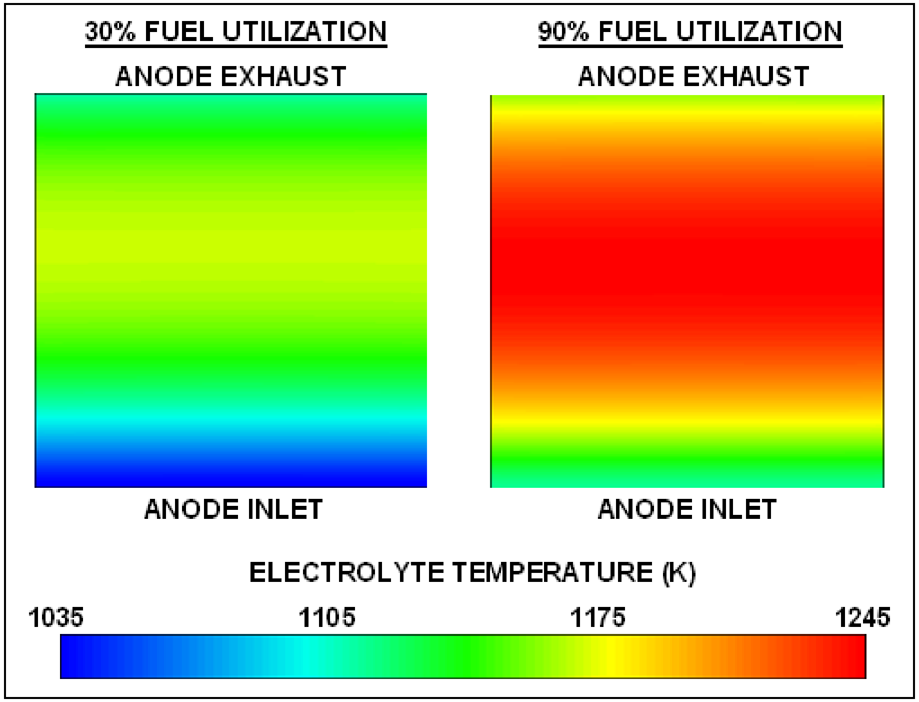
FUEL FLOW RATE



Hydrogen Distribution at Electrolyte vs. Fuel Utilization



Electrolyte Temperature Distribution vs. Fuel Utilization

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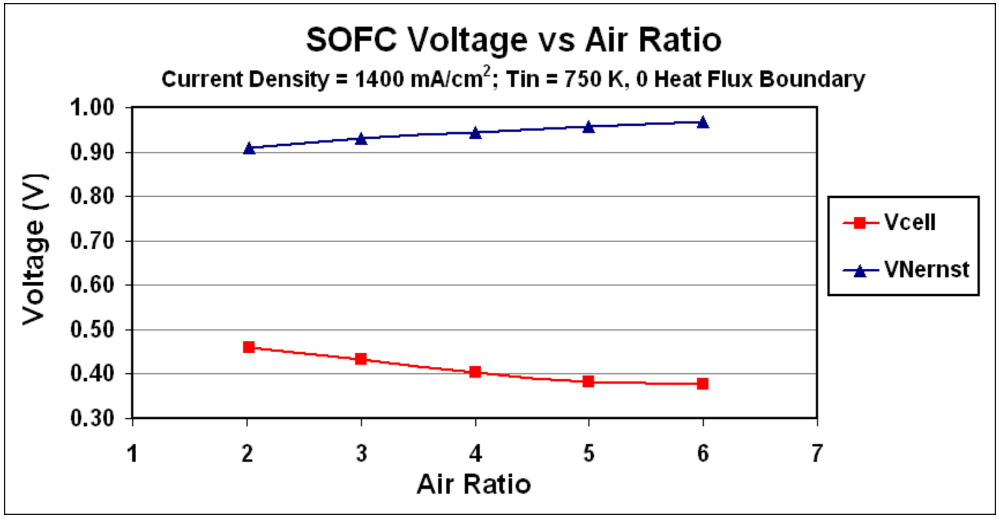
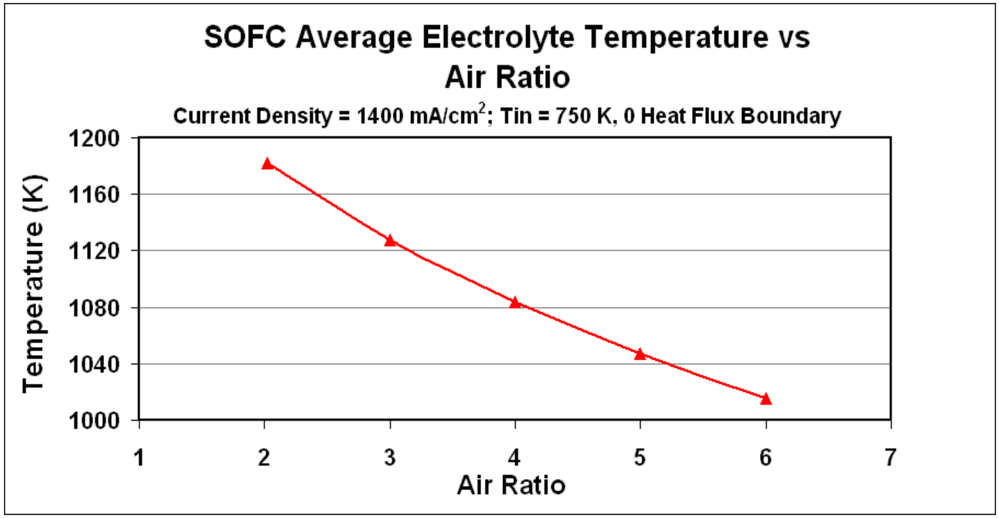
AIR FLOW RATE





- The **air ratio**, R, is the ratio of the air mass flow rate supplied divided by the air mass flow rate required.
- **R** was varied from **2 to 6**
- During operation with a fixed fuel utilization factor of 70%, the air-to-fuel ratio increased from approximately 48 when the air ratio was 2.0 to a value of 143 when R was equal to 6.0.
- The significantly greater mass flow on the cathode side absorbed more heat from the electrolyte.
- When the air flow rate was doubled or tripled, there was a larger drop in the electrolyte temperature than when the fuel flow rate was increased by the same ratio.
- The reduction in temperature with higher air ratios did result in an increase in the Nernst voltage.
- Despite the increase in the oxygen concentration at the cathode-electrolyte interface, increasing the air flow resulted in an even greater increase in the cell's Ohmic losses (due to the drop in temperature) and caused the cell voltage to drop.

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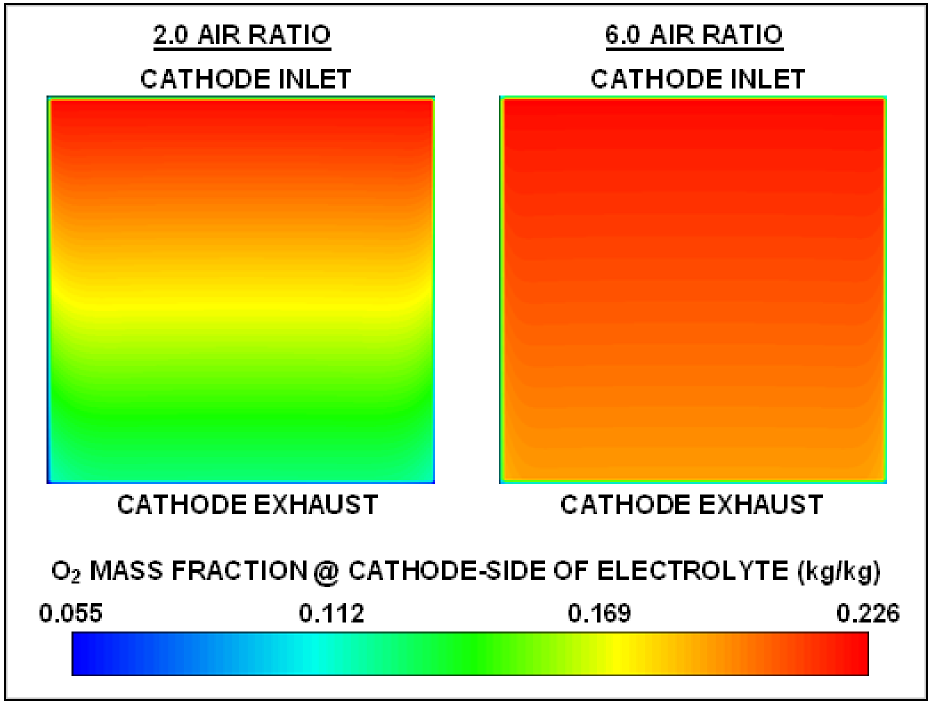
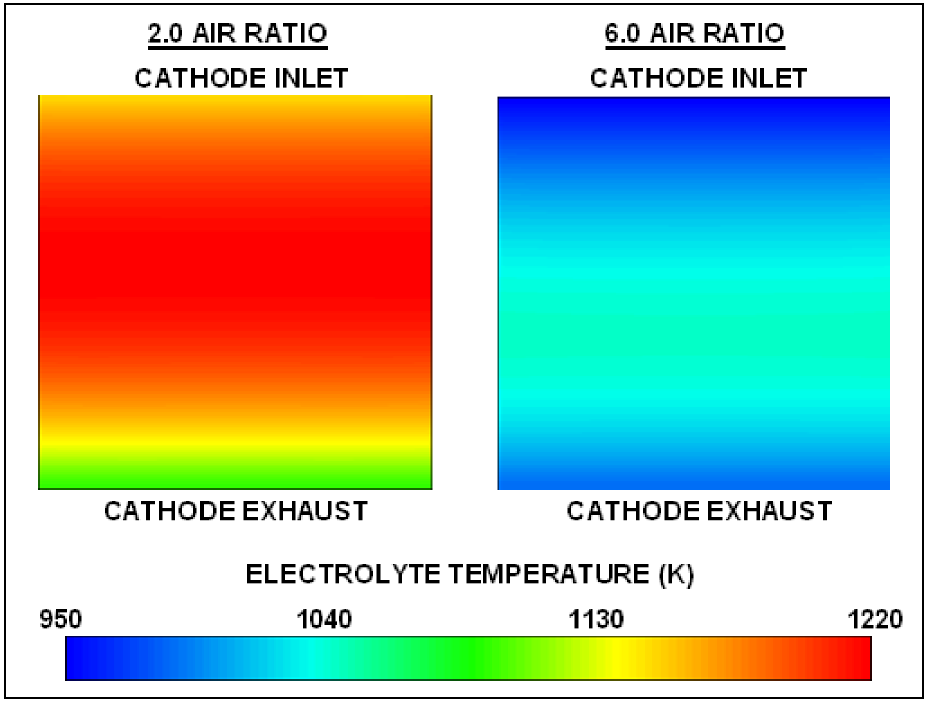
Air Flow Rate



Oxygen Distribution at Electrolyte vs. Air Ratio



Electrolyte Temperature Distribution vs. Air Ratio

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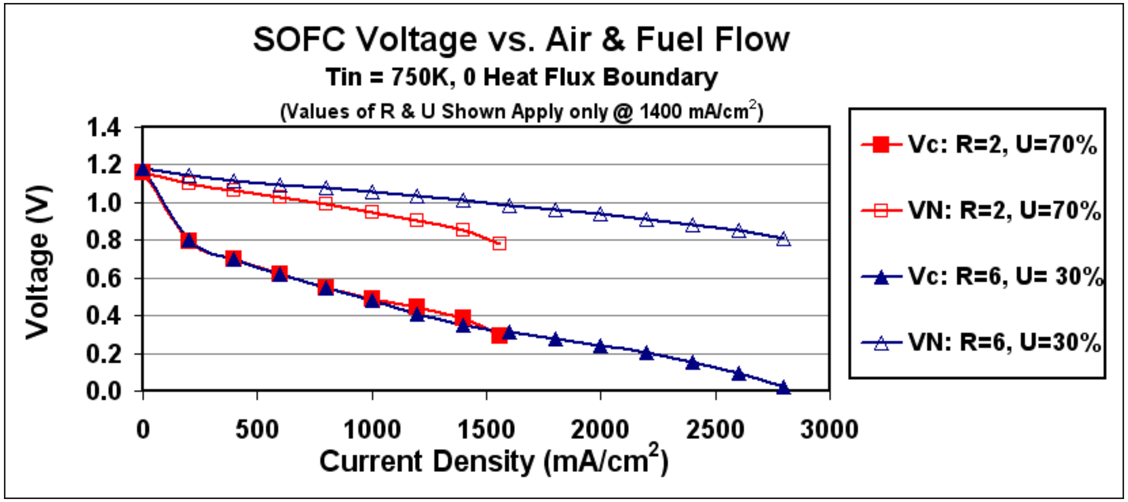
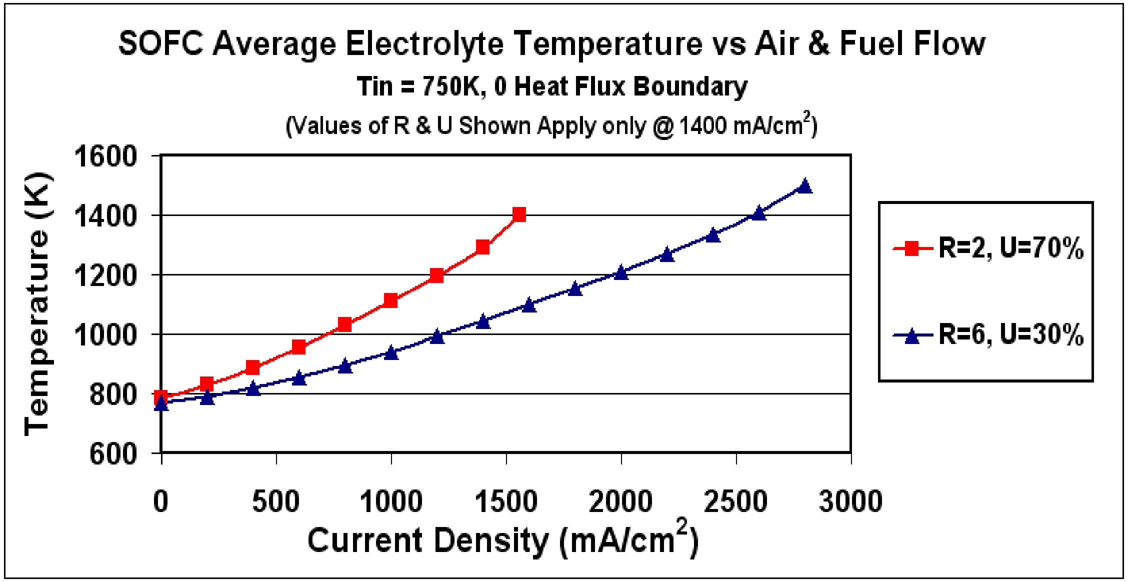
FUEL & AIR FLOW RATE





- ➢ Due primarily to the reduction in temperature, operation with an air ratio, R, of 6.0 and a fuel-utilization factor, U, of 30% resulted in a higher Nernst voltage than operation with an air ratio of 2.0 and a fuel-utilization factor of 70%.

- ➢ The beneficial effects of the increased Nernst voltage and reactant concentrations with increaded air & fuel flow were all but nullified by the detrimental effects of the reduced cell temperature, and the cell voltage values for both sets of air and fuel flow rates were virtually identical up to a current density of approximately 1500 mA/cm^2.

- ➢ After this point, the increased air and fuel flow during operation with R = 6 and U = 30% did prevent the drop in cell voltage ordinarily associated with concentration losses, and the operating range of the cell was significantly increased.

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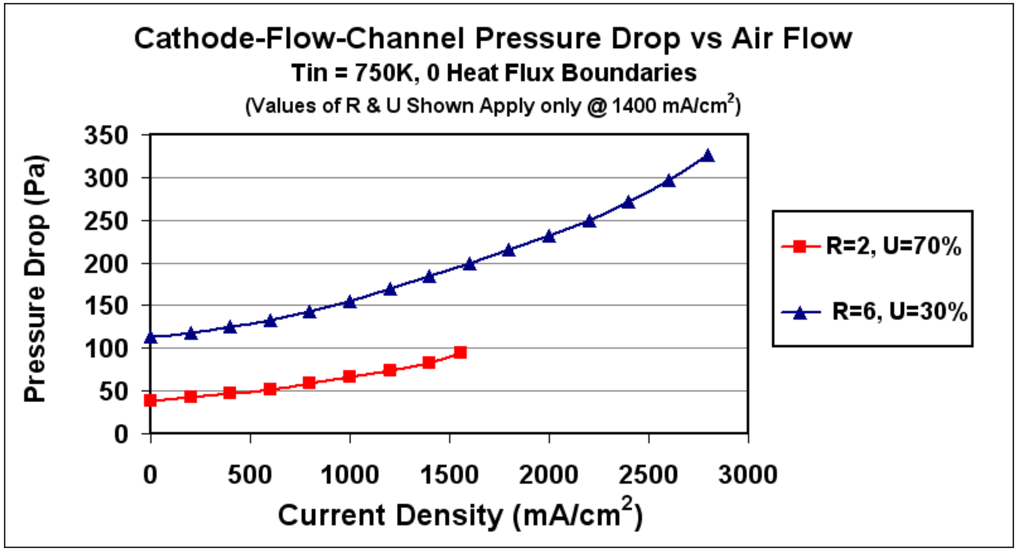
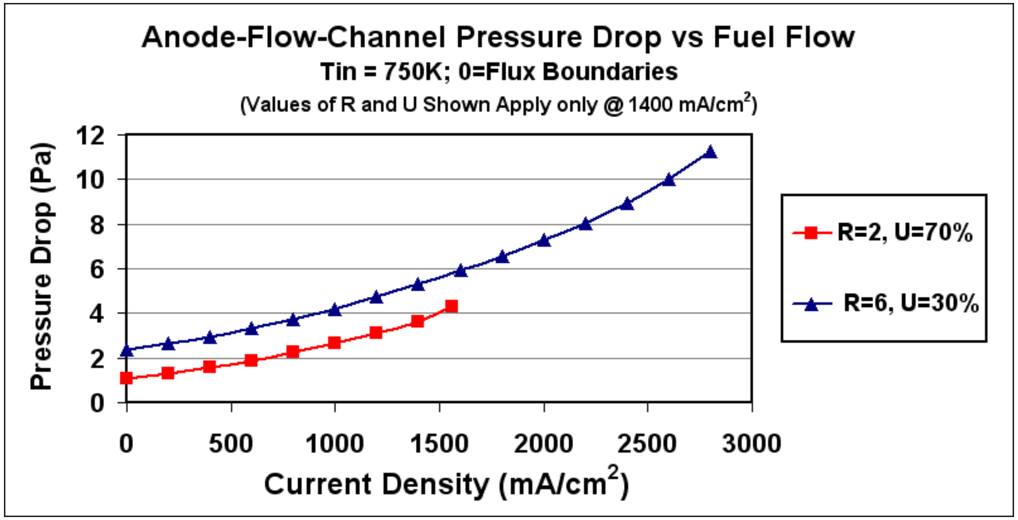
FUEL & AIR FLOW RATE





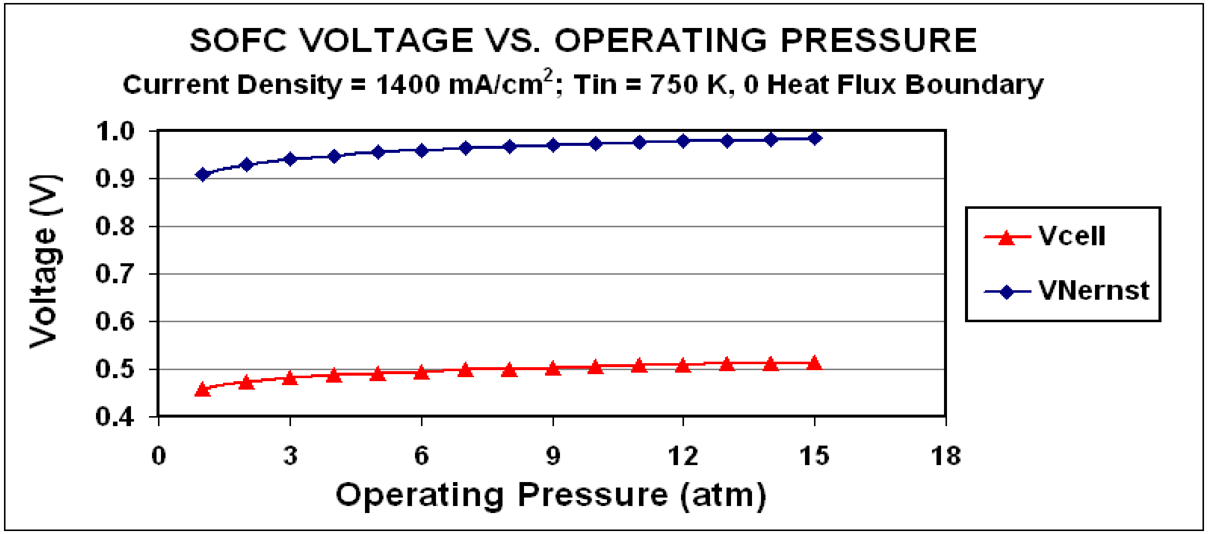
- When the air ratio was increased and more air was supplied to the cell, <u>the pressure drop within the cathode-flow channels increased</u>.

- As the <u>current density was increased with a fixed air mass flow rate</u>, <u>this pressure drop increased</u> due to the higher operating temperatures and the resulting increased expansion of the air, which resulted in higher fluid velocities within the cathode-flow channels and increased friction losses.

- When the <u>fuel utilization was reduced</u> and more fuel was supplied to the cell, the <u>pressure drop within the anode-flow channels increased</u>.

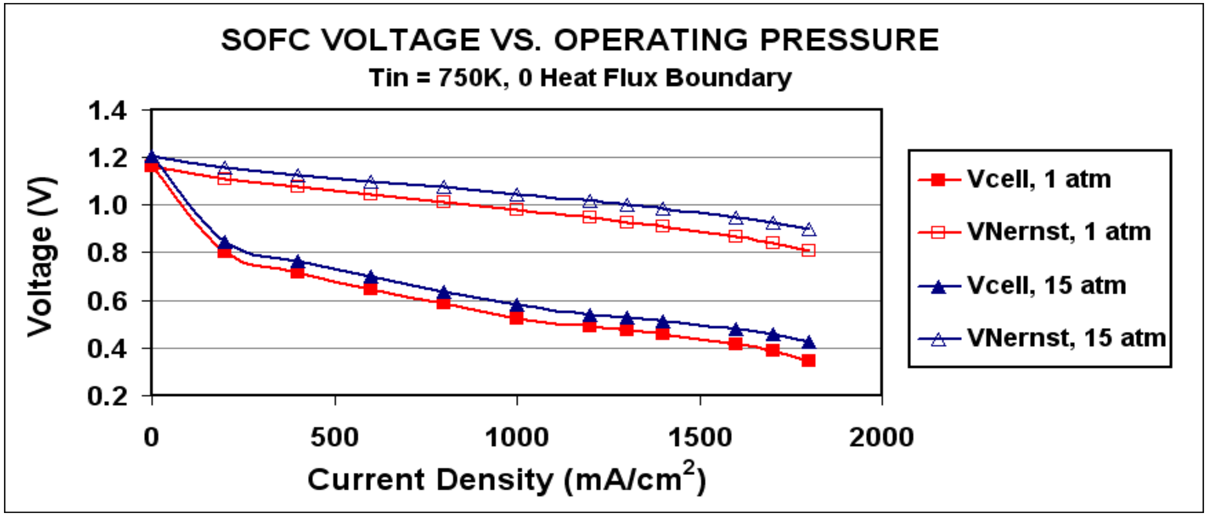
- As the <u>current density was increased with a fixed fuel mass flow rate</u>, <u>this pressure drop increased</u> due to the higher operating temperatures and the resulting increased expansion of the fuel during operation at higher current densities, which resulted in higher fluid velocities within the anode-flow channels and increased friction losses.

OPERATING PRESSURE



SOFC VOLTAGE VS. OPERATING PRESSURE

Current Density = 1400 mA/cm^2; Tin = 750 K, 0 Heat Flux Boundary



SOFC VOLTAGE VS. OPERATING PRESSURE

Tin = 750K, 0 Heat Flux Boundary

- ➢ Operating Pressure varied from **1 to 15 atm**.
- ➢The Nernst voltage produced by an SOFC increases with the partial pressure of the reactants.
- ➢ This also results in an increase in the cell voltage.

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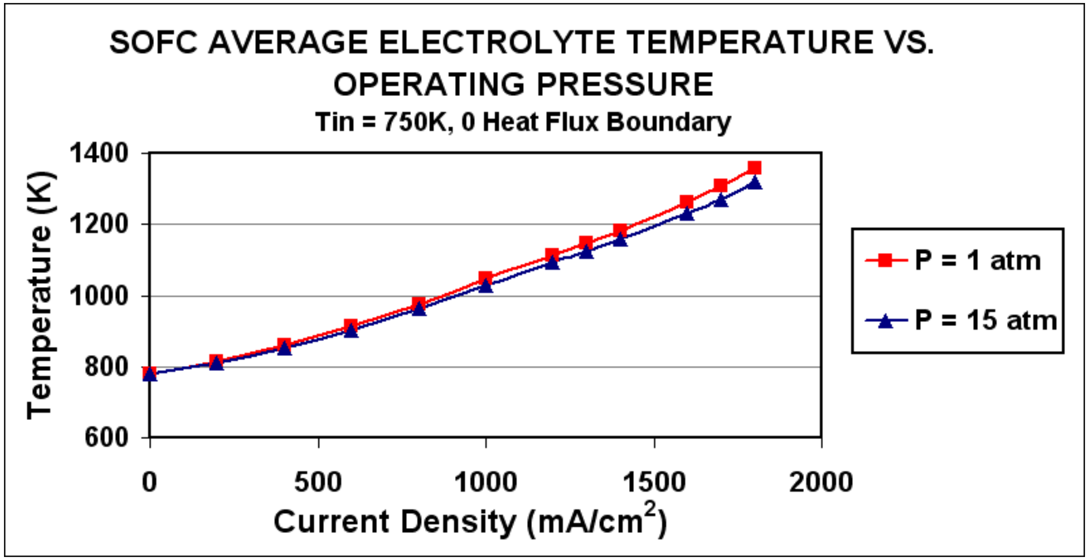
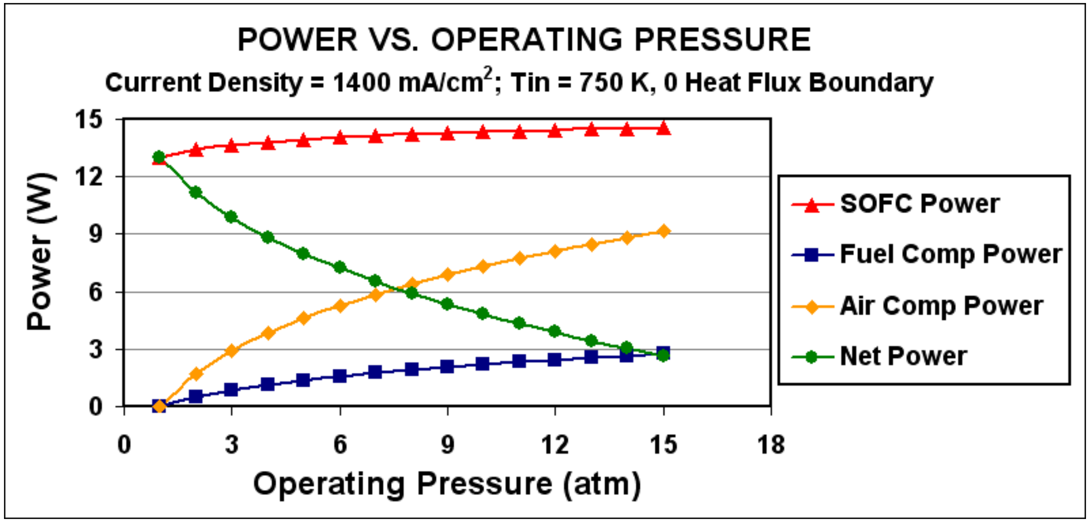
OPERATING PRESSURE





- ➢ As the cell voltage increased with a constant current, less heat was generated in the cell (because more useful work was performed) and there was a slightly lower electrolyte temperature.
- ➢Compressing the incoming fuel and air also adds heat to these gases, which could enable them to be supplied to a fuel cell at an increased temperature. This would tend to increase electrolyte temperatures, anode and cathode exhaust temperatures, and possibly the cell voltage.
- ➢ When the air and fuel compressor electrical loads are considered, the net power produced was reduced as the operating pressure increased.
- ➢ Using a pressurized cell is recommended only if there is another reason to compress the fuel and air, such as to permit a gas turbine to be used as part of an SOFC-hybrid system.

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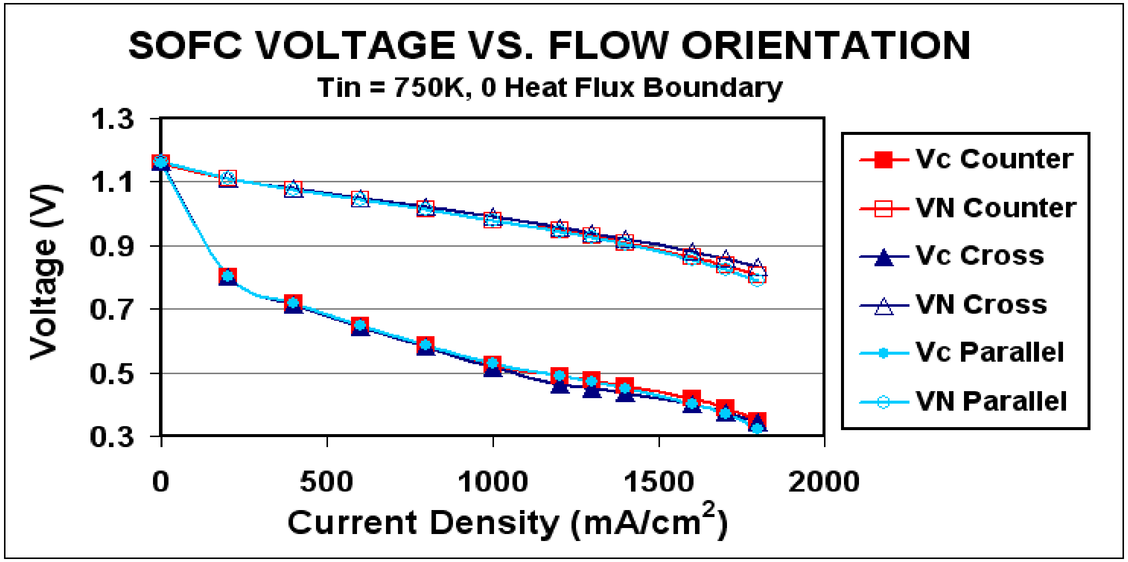
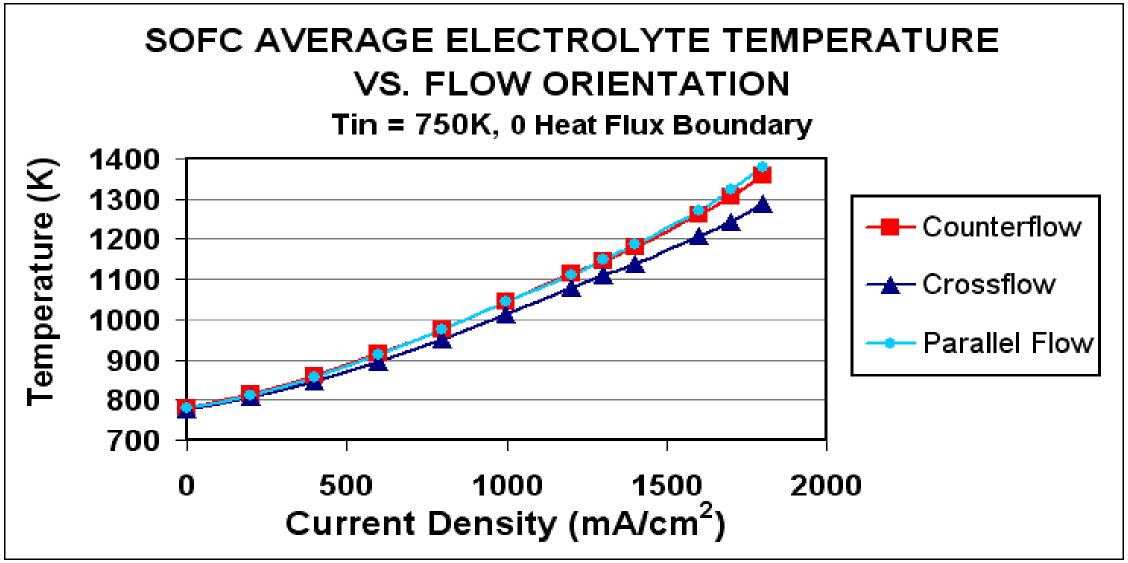
FLOW ORIENTATION


SOFC VOLTAGE VS. FLOW ORIENTATION

Tin = 750K, 0 Heat Flux Boundary


SOFC AVERAGE ELECTROLYTE TEMPERATURE VS. FLOW ORIENTATION

Tin = 750K, 0 Heat Flux Boundary

- Simulations were conducted with **counterflow, crossflow, and parallel-flow configurations**.

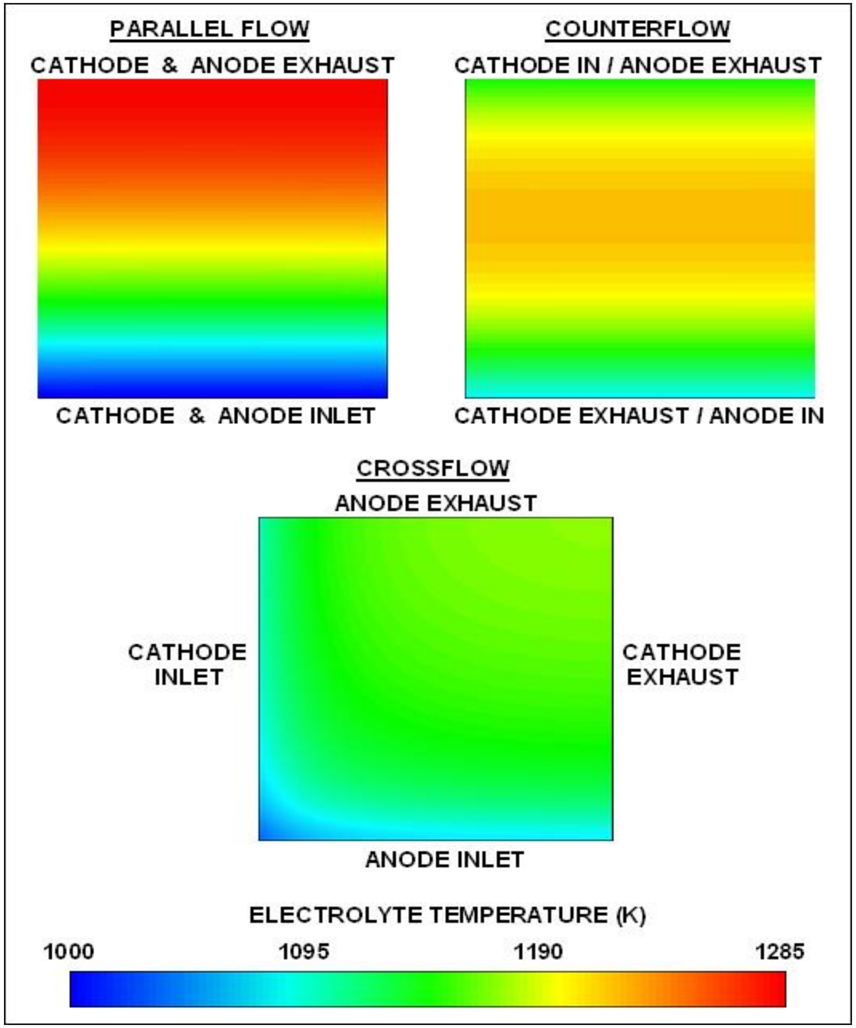
- During operation with lower current densities, cell-voltage values for all three configurations were virtually identical.

- During operation with higher current densities, the counterflow arrangement did produce slightly higher cell voltages.

- With the exception of a slight divergence at the high-current-density end of the curve, the average electrolyte temperatures with the counterflow and parallel-flow configurations were almost identical and were generally slightly greater than the average electrolyte temperature with the crossflow arrangement.

- A higher temperature results in more waste heat for use in a hybrid system.

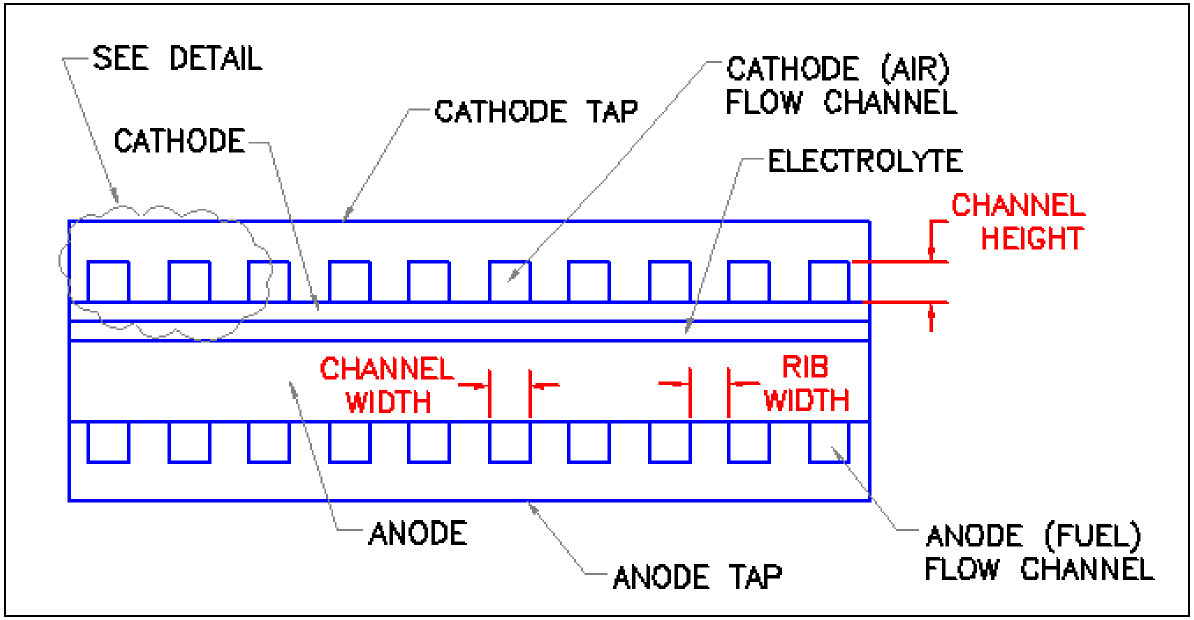
FLOW ORIENTATION



SOFC Electrolyte Temperature vs. Flow Orientation (1400 mA/cm^2)

- ➢ The differential temperature across the electrolyte with counterflow was significantly less than that of the parallel-flow cell and was close to the maximum differential temperature across the electrolyte in the crossflow cell.
- ➢ Limiting the differential temperature across various parts of a fuel cell reduces stresses resulting from uneven thermal expansion.
- ➢ The counterflow arrangement was considered to be the preferred choice for the planar SOFC analyzed.

FLOW-CHANNEL DIMENSIONS



SOFC Flow-Channel Arrangement

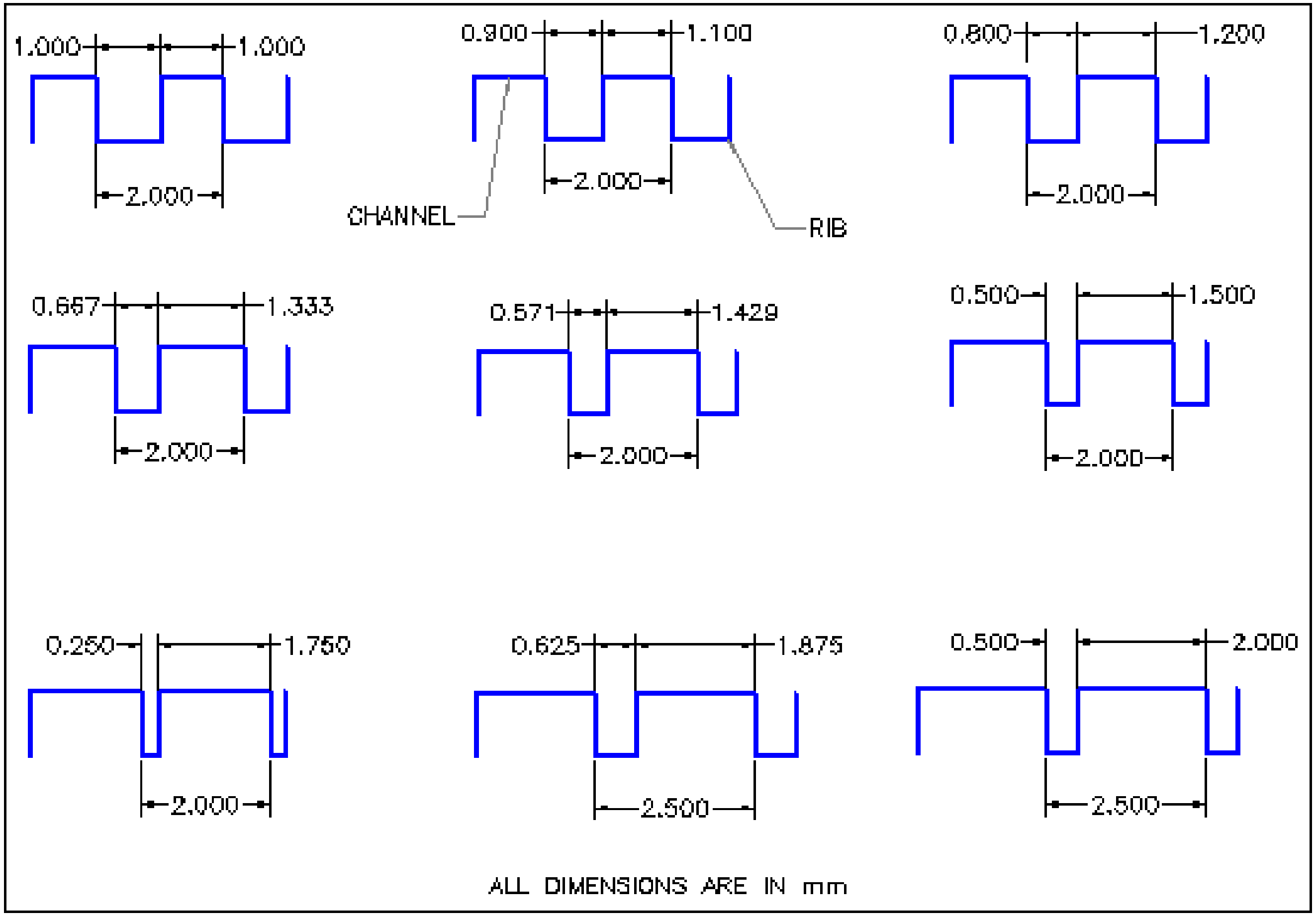
➢ The effect of <u>flow-channel size</u> was determined by performing a series of analyses with various channel dimensions.

➢ To be able to differentiate between the effects of changes in the channel width and those resulting from changes in the channel height, this study was divided into two parts:

1. <u>Simulations performed with different channel and rib widths</u> but with a constant channel height.

2. <u>Simulations performed with different channel heights</u> but with constant channel and rib widths.

Flow-Channel and Rib Width

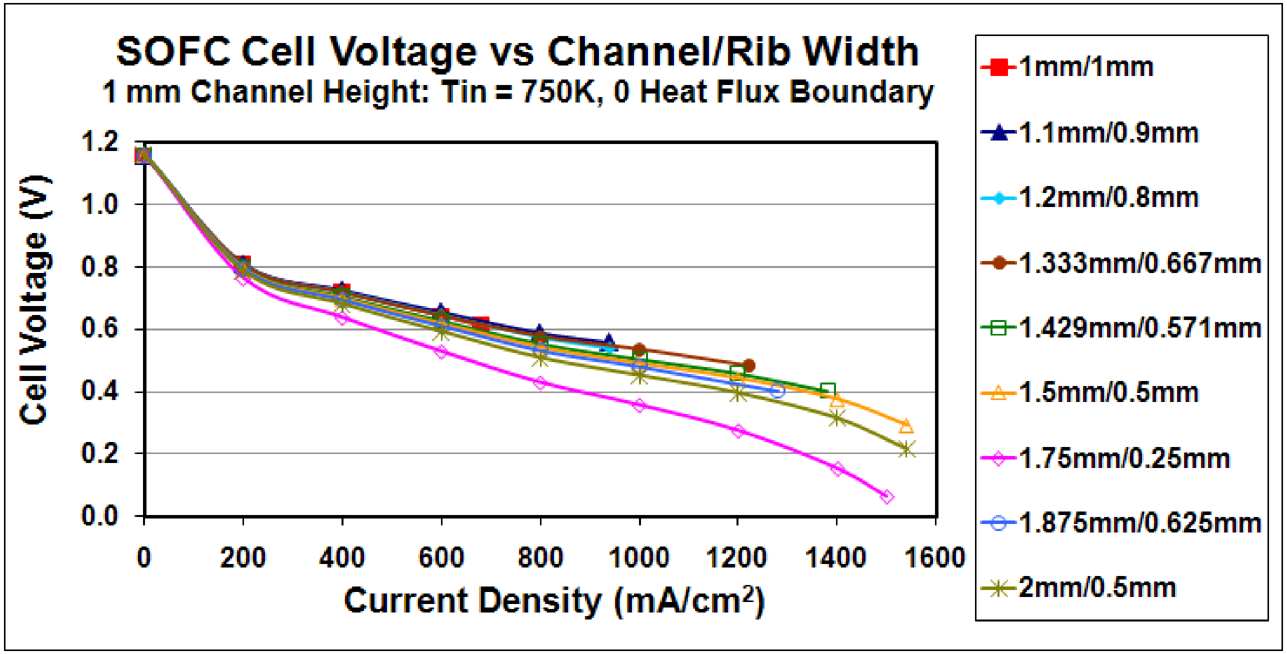


ALL DIMENSIONS ARE IN mm

SOFC Flow-Channel / Rib Width Detail
(1 mm Channel Height)

- ➢ Nine different channel- and rib-width combinations were analyzed.
- ➢ The channel and rib width selected resulted in a whole number of complete channels across the width of the cell.
- ➢ The height of all of the channels was set equal to 1 mm.

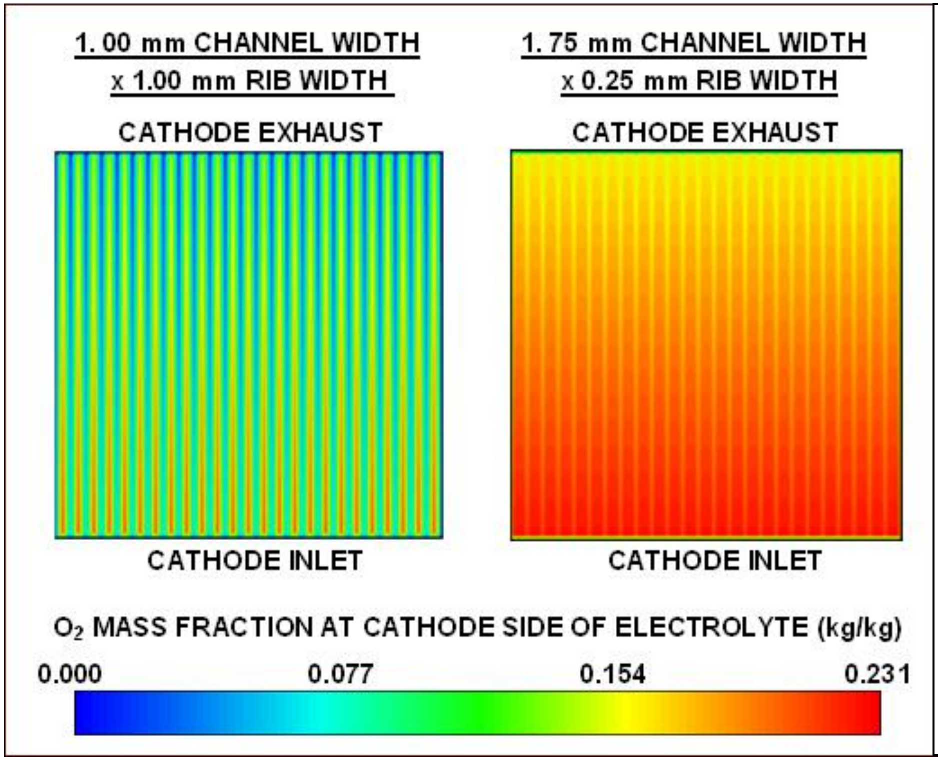
FLOW-CHANNEL AND RIB WIDTH



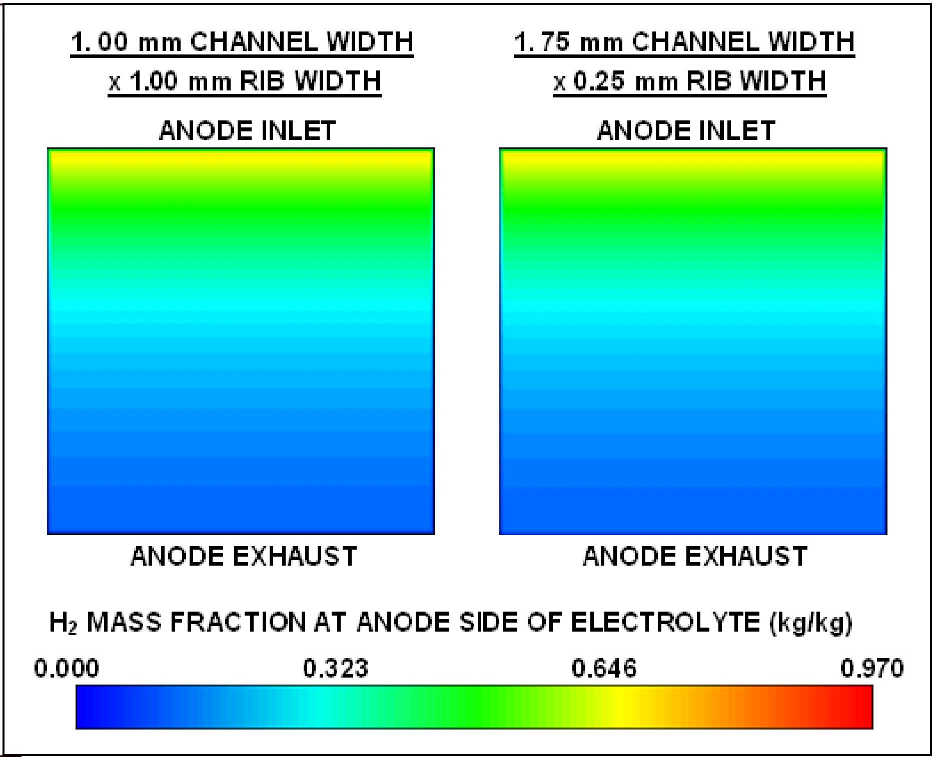
- Larger rib widths reduced the resistance to the electrical current conducted through the ribs.
- increasing the rib width enabled the cell to develop a higher cell voltage.
- Wider ribs also reduced the area over which incoming oxygen was in contact with the upper surface of the cathode and made it more difficult for the oxygen to diffuse through the cathode.
- Due to the improved oxygen diffusion, the operating range in terms of current density was typically higher for the cells with thinner ribs.
- Rib width had little effect on the diffusion of hydrogen through the anode. This was expected due to the relatively low diffusion resistance of hydrogen when compared to that of oxygen.

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

FLOW-CHANNEL AND RIB WIDTH

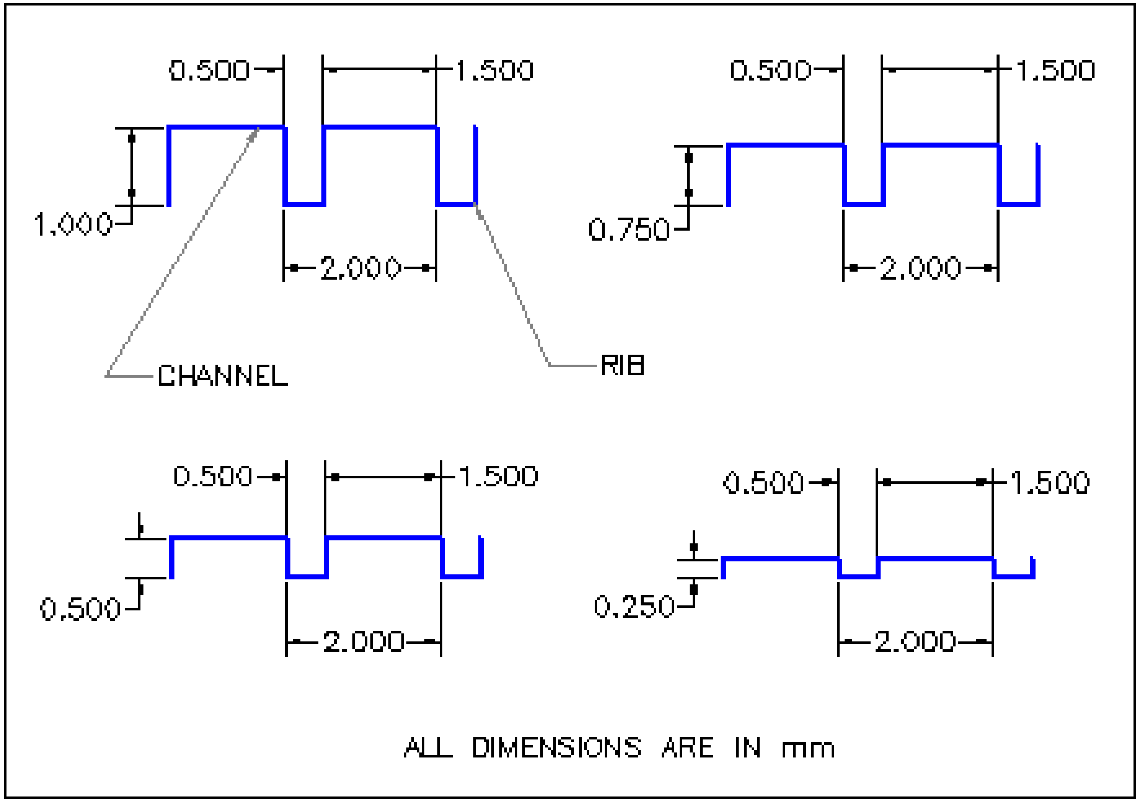


Effect of Channel / Rib Width on O_2 Diffusion Through Cathode (Current Density = 680 mA/cm^2)



Effect of Channel / Rib Width on H_2 Diffusion Through Anode (Current Density = 680 mA/cm^2)

FLOW-CHANNEL HEIGHT

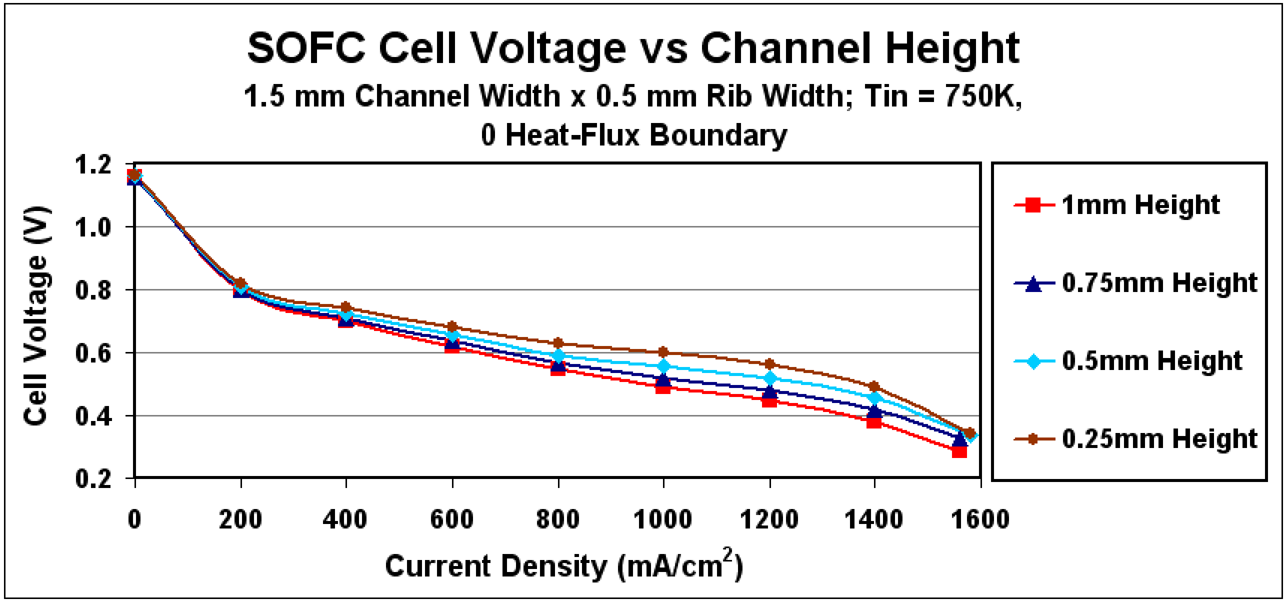


SOFC Cell Flow-Channel Height Detail (1.5 mm Channel & 0.5 mm Rib Widths)

- ➢ Four different flow-channel heights were evaluated.
- ➢ The channel and rib widths were set equal to 1.5 mm and 0.5 mm, respectively.

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

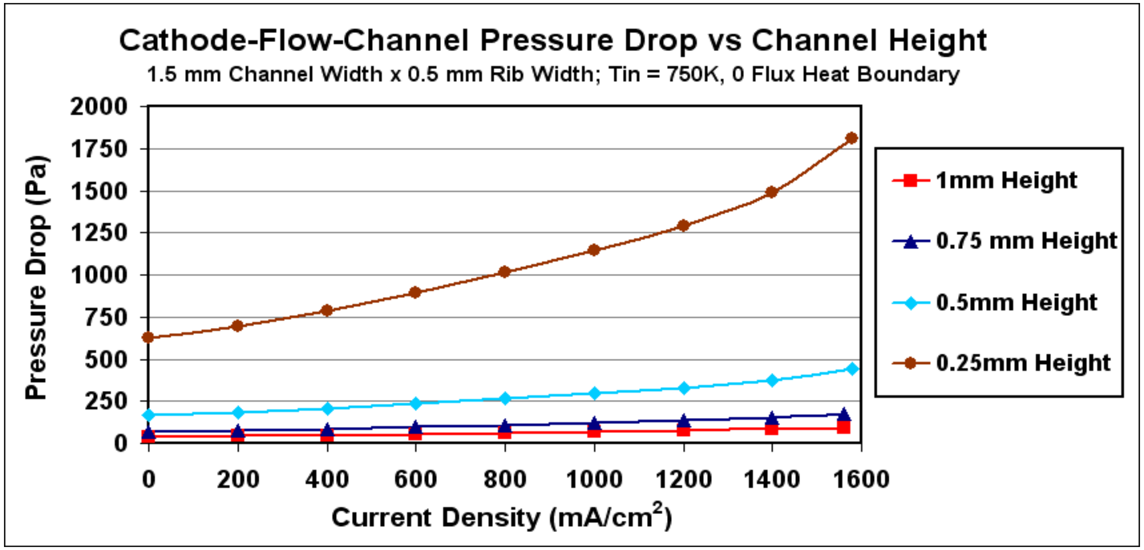
FLOW-CHANNEL HEIGHT

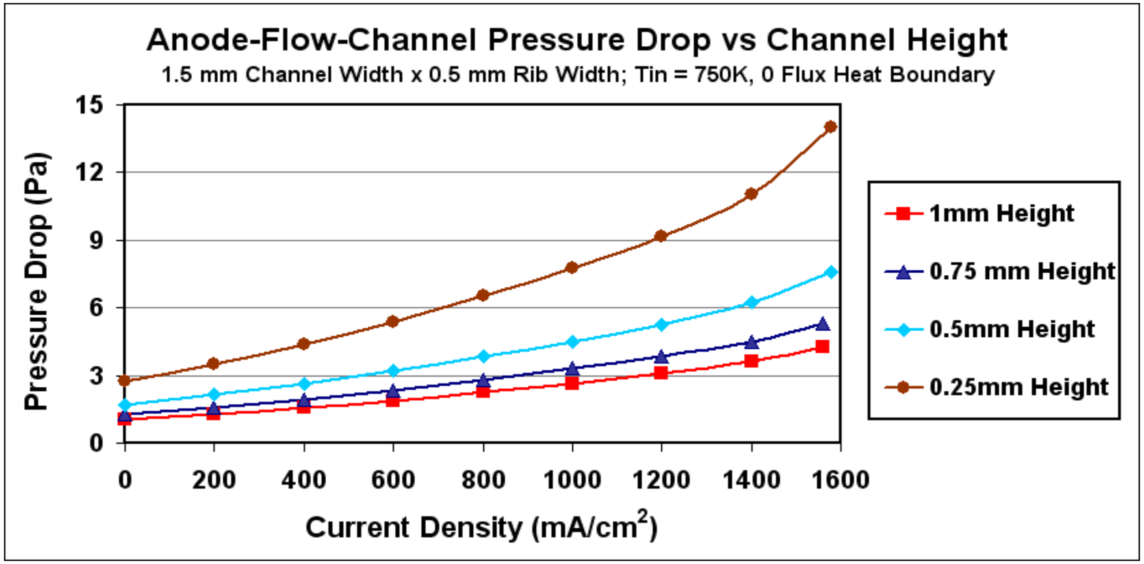


- At any given current density, the <u>cell voltage developed increased</u> as the <u>channel height was reduced</u> due to the reduced electrical resistance in the cells with shorter ribs.

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

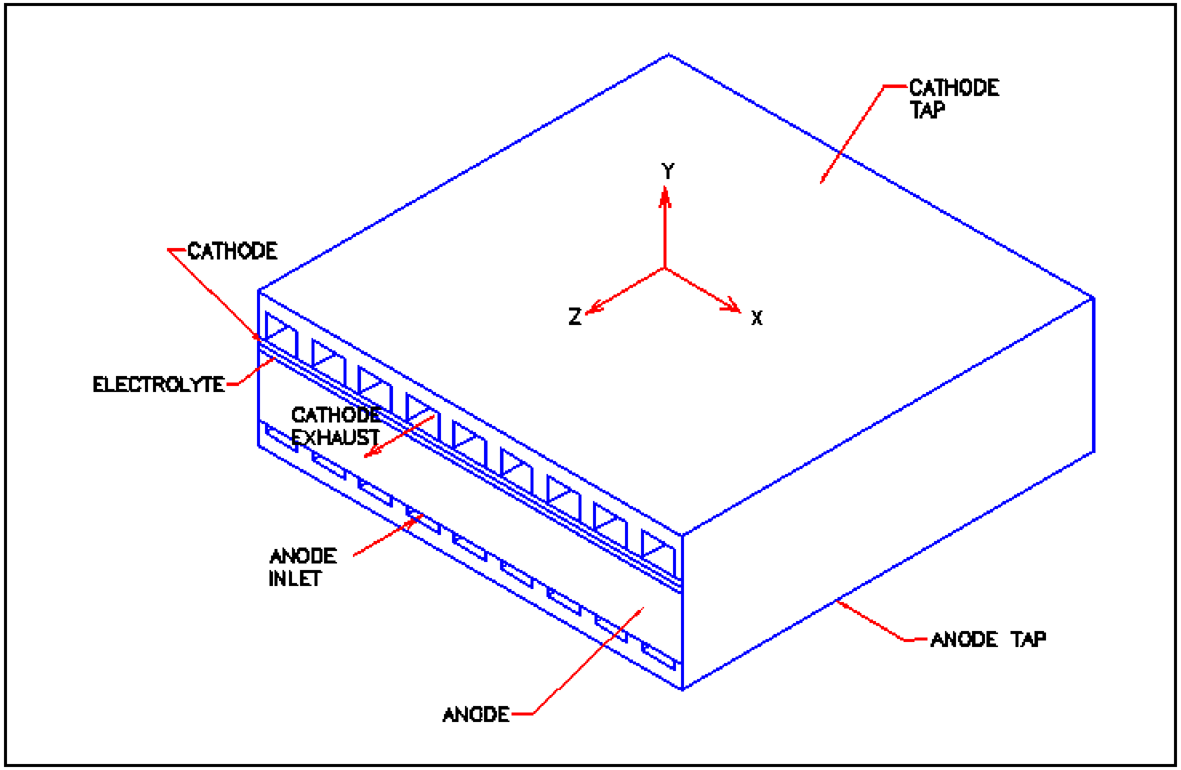
FLOW-CHANNEL HEIGHT





- ➢ A disadvantage of reduced flow-channel height is an increased pressure drop within the flow channels.
- ➢ The magnitude of the pressure drop in the cathode-flow channels was significantly higher than that in the anode-flow channels.
- ➢ This was due, primarily, to the relatively high air/fuel ratio of 48 in terms of mass that was maintained during the flow-channel study, which is typical of fuel-cell operation and resulted in a much higher air-flow rate when compared to the flow rate of the fuel.

OPTIMIZED SINGLE-CELL CONFIGURATION



Final SOFC Single-Cell Configuration

- A flow-channel width of **1.333 mm** with the corresponding rib width of **0.667 mm** was selected because it resulted in the production of reasonably high cell-voltage values and in an operating range with current densities as high as 1200 mA/cm^2.

- The channel height selected for the anode-flow channels was **0.25 mm,** which resulted in the highest cell voltage when compared to the other channel heights evaluated. The pressure drop in the anode-flow channels with this height did not exceed 15 Pa.

- On the cathode side, the pressure drop with a 0.25 mm channel height would exceed 1800 Pa. To limit this pressure drop to less than 200 Pa, a height of **0.75 mm** was selected for the cathode-flow channels.

CONCLUSIONS OF SINGLE-CELL PARAMETRIC STUDY

Thermal Boundary Conditions

- As predicted by theory, conditions resulting in higher cell temperatures typically resulted in lower thermodynamically reversible or Nernst voltages. These higher temperatures were achieved by changing the SOFC's boundary conditions to reduce or eliminate heat transfer to the surroundings and by preheating the fuel and air supplied to the cell.

- Because the higher temperatures also reduced Ohmic and, when operating with low to moderate current densities, activation losses, the cell voltages being produced often increased.

Air & Fuel Flow Rates

- Increasing air and fuel concentrations also increased the Nernst voltage, together with the range of current densities over which the cell could operate.

- Due to the cooling created by the increased flow rates, the improvement in the cell voltage produced was either reduced (in the case of increased fuel flow) or eliminated (in the case of increased air flow).

Air & Fuel Inlet Pressures

- Increasing the pressure at which fuel and air were supplied to the SOFC resulted in higher cell voltages.

- This benefit was eliminated when the air- and fuel-compressor electrical loads were considered.

- It is beneficial to pressurize an SOFC only when the compressed gas will be used for another purpose.

Air & Fuel Flow Orientation

- A counterflow arrangement resulted in cell voltages and electrolyte temperatures that were almost identical to or slightly greater than values with parallel-flow and crossflow configurations.

- The electrolyte's differential temperature in the counterflow cell was significantly less than the value in the parallel-flow cell and was close to the maximum differential temperature across the electrolyte in the crossflow cell, which helps to limit thermal stress.

CONCLUSIONS OF SINGLE-CELL PARAMETRIC STUDY (continued)

Air & Fuel Flow-Channel Dimensions

- The use of wider ribs separating adjacent flow channels reduced the resistance to the electrical current conducted through the ribs.

- Because it also reduced the area over which incoming oxygen was in contact with the electrode surfaces, the use of wider ribs impeded the diffusion of oxygen through the cathode.

- A similar effect did not occur on the diffusion of hydrogen through the anode.

- Reducing channel height reduced electrical resistance.

- It also increased the pressure drop within the channels. This effect was more pronounced in the cathode flow channels due the significantly larger air flow rate when compared to the fuel flow rate.

Overall Result

- Based on all of the aforementioned CFD simulations, **an optimum cell configuration was established.**

- It is believed that the process described could be repeated by fuel-cell designers to better predict the effect of various changes on the performance of a cell before it is manufactured and tested.

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

SOFC MULTI-CELL ANALYSES

- OBJECTIVE
- SOFC MULTIPLE-CELL ANALYSIS
- MULTI-CELL ADJUSTMENT FACTORS
- CONCLUSIONS OF MULTI-CELL ANALYSIS

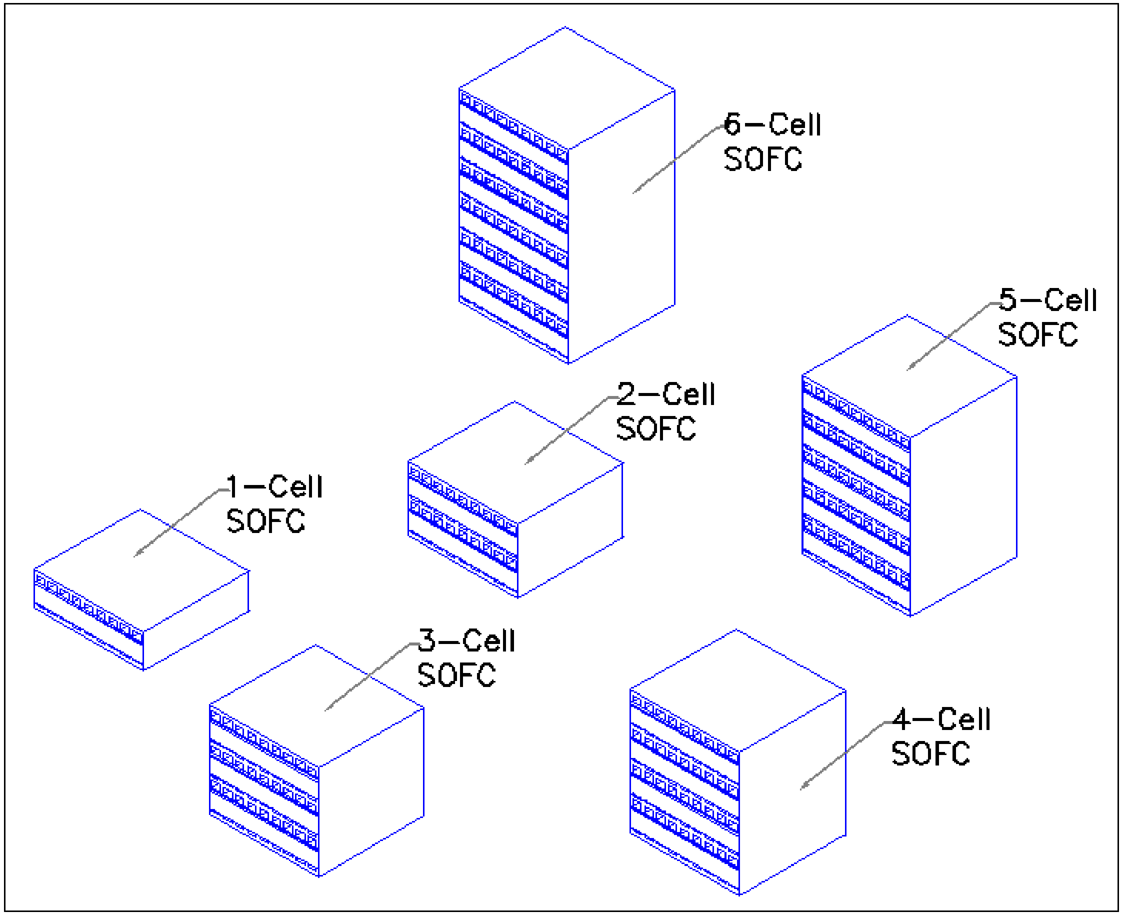
OBJECTIVE OF MULTI-CELL STUDY

- A typical single-cell fuel cell is capable of producing less than one volt of direct current.
- To produce the voltages required in most industrial applications, many individual fuel cells must typically be stacked together and connected electrically in series.
- Computational fluid dynamics (CFD) can be helpful to predict fuel-cell performance before a cell is actually built and tested.
- To perform a CFD simulation using a 3-dimensional model of an entire fuel-cell stack would require a considerable amount of time and multi-processor computing capability that may not be available to the designer.
- To eliminate the need to model an entire multi-cell assembly, a study was conducted to determine the incremental effect on fuel-cell performance of adding individual solid-oxide fuel cells (SOFC) to a multi-fuel-cell stack.
- As part of this process, a series of simulations was conducted to establish a CFD-nodal density that would produce reasonably accurate results but that could also be used to create and analyze the relatively large models of the multi-cell stacks.

SOFC MULTI-CELL ANALYSES

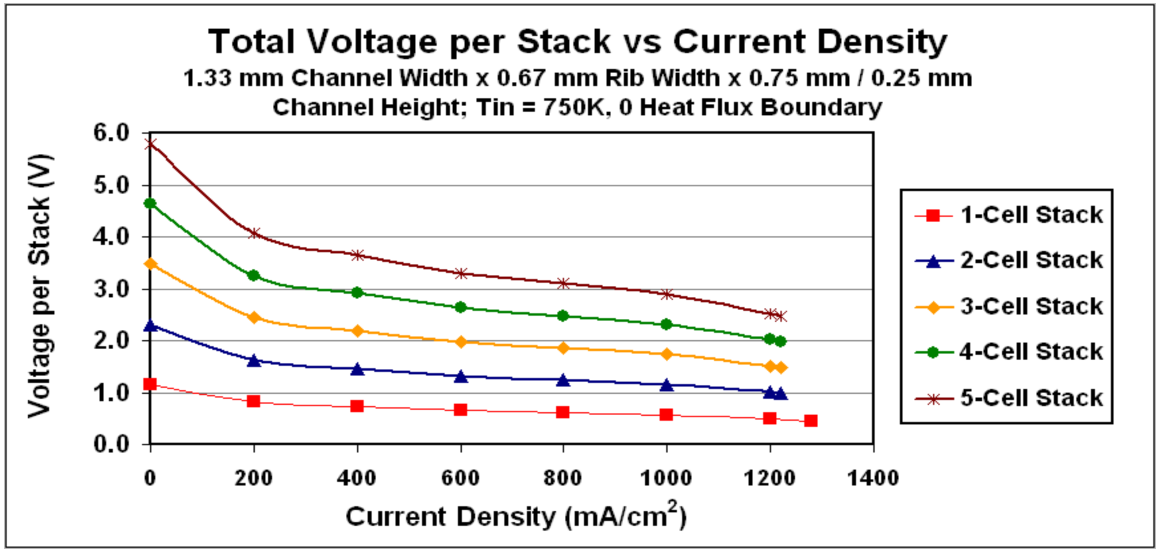
Using the optimized single-cell geometry described previously, five different multi-cell stacks containing from 2 to 6 cells were modeled using CFD and analyzed.

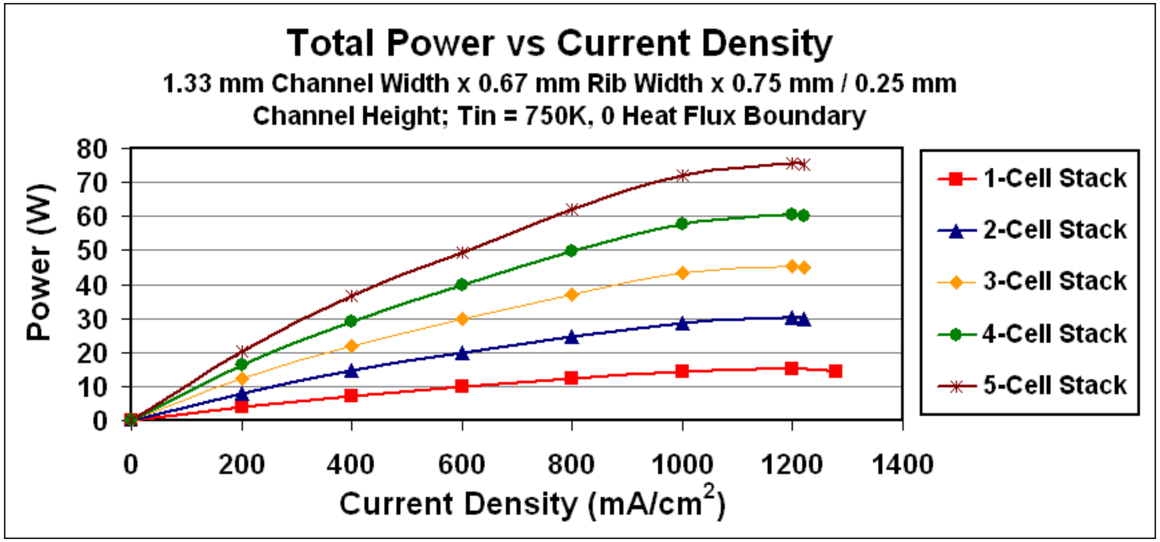
CFD Model Size vs # Fuel Cells in Stack			
# Fuel Cells in Stack	Cell Area	# of CFD Finite-Volume Cells	# of CFD Nodes
	mm x mm		
1	50 x 50	204,000	497,949
2		384,000	267,321
3		564,000	728,577
4		744,000	959,205
5		924,000	1,189,833
6		1,104,000	1,420,461



SOFC Cell Stacks Evaluated

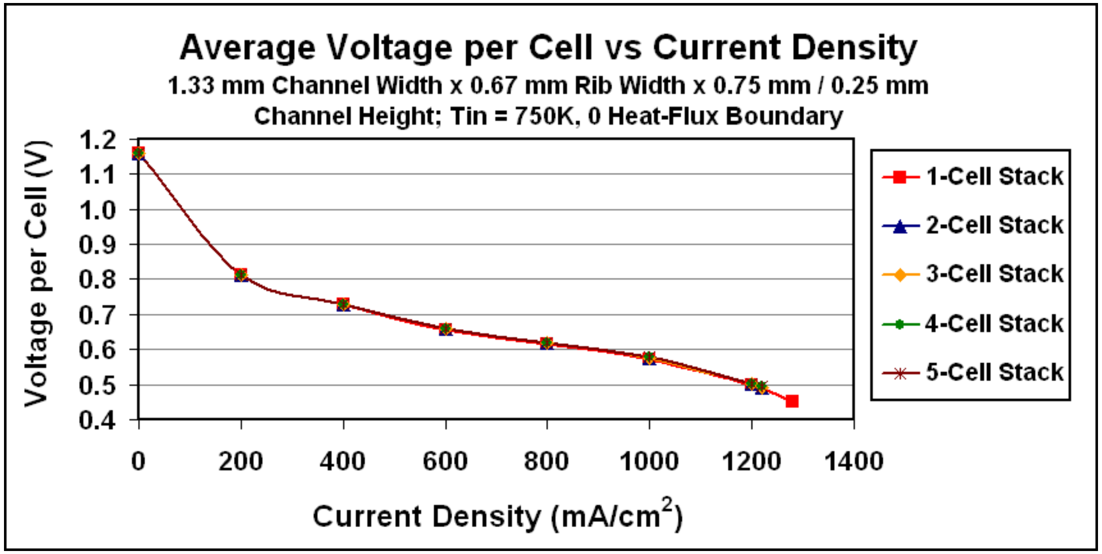
SOFC MULTI-CELL ANALYSES – CELL VOLTAGE

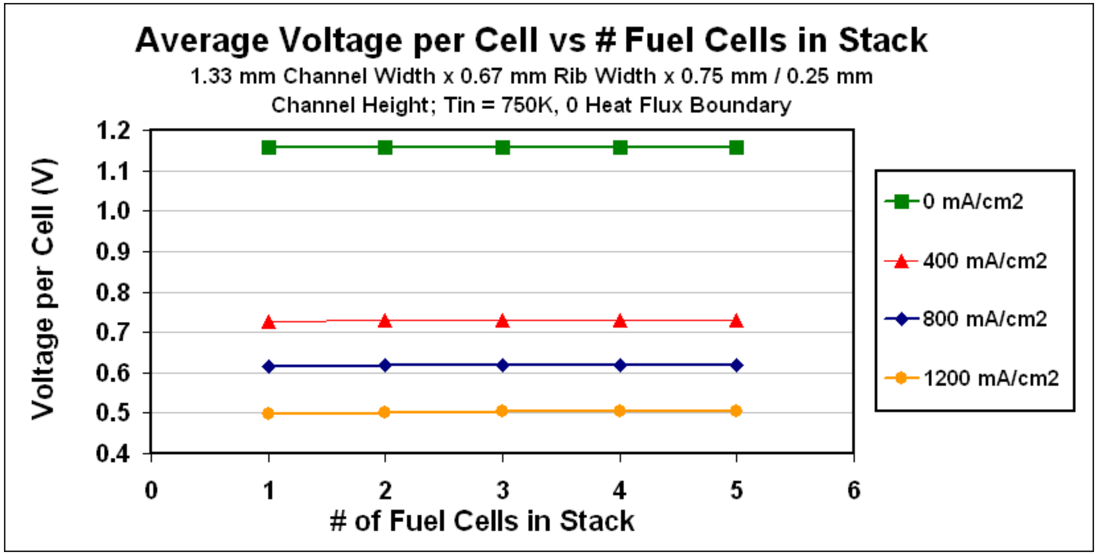




- Because of the size of the 6-cell stack CFD model (1.1 million finite-volume cells, 1.42 million nodes), data was obtained for this stack only during operation with a current density of 1200 mA/cm^2

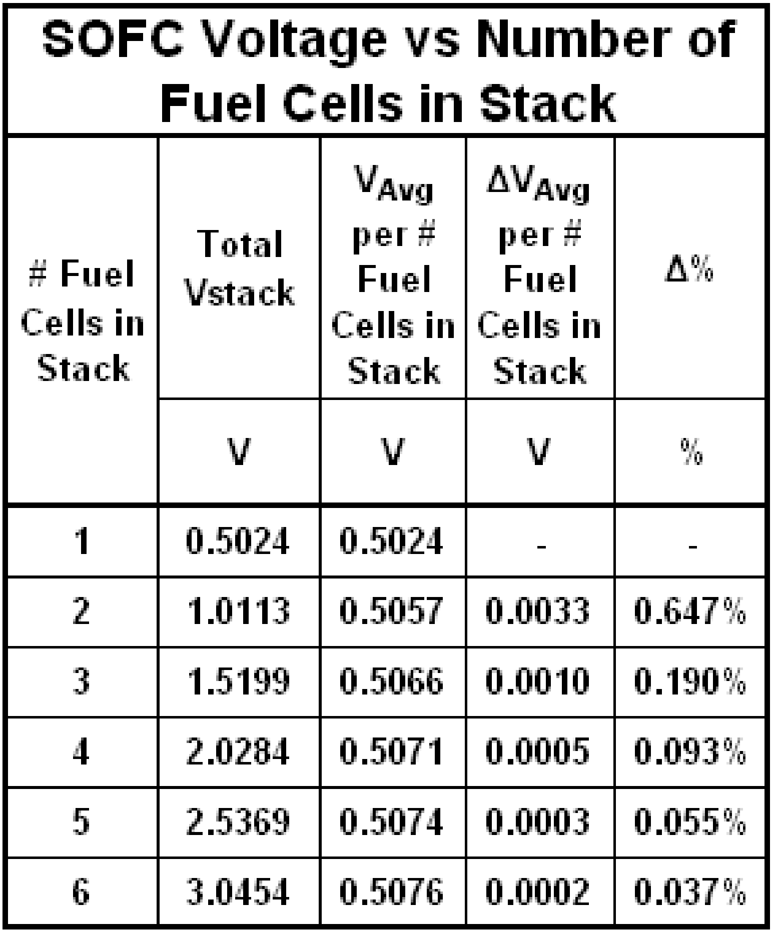
SOFC MULTI-CELL ANALYSES – CELL VOLTAGE





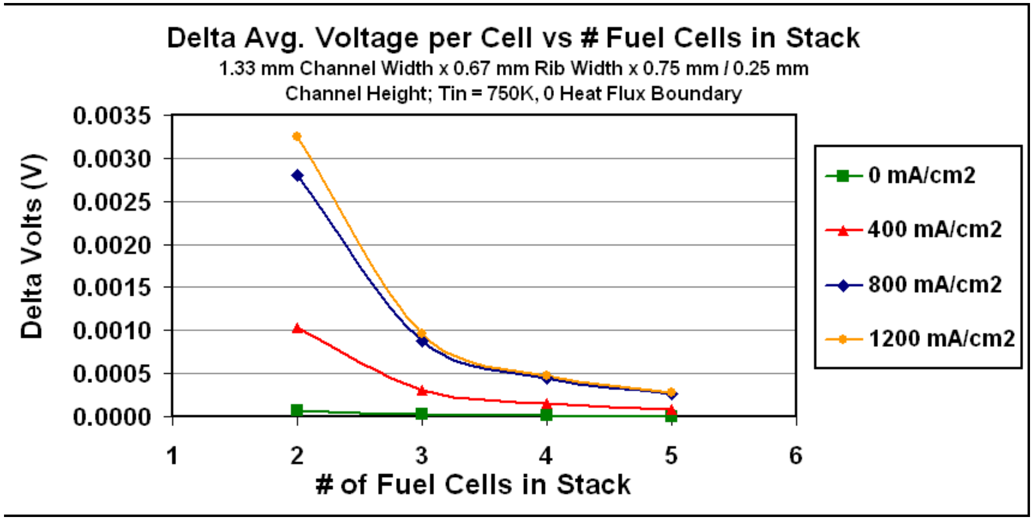
- The average voltage produced by each cell in the stacks analyzed remained relatively constant or increased very slightly as the number of fuel cells in the stack increased.

SOFC MULTI-CELL ANALYSES – CELL VOLTAGE



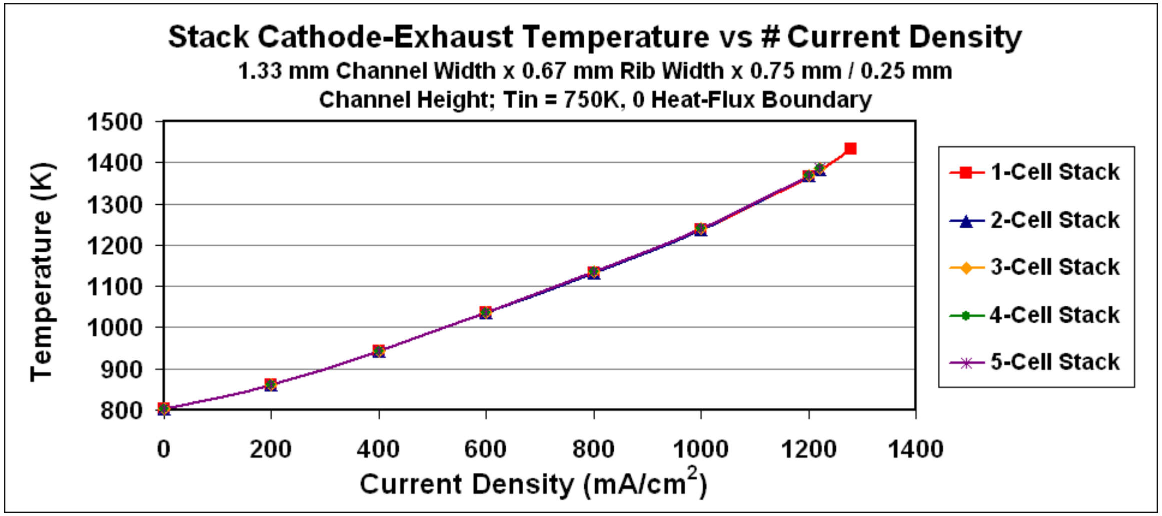
SOFC Voltage vs Number of Fuel Cells in Stack

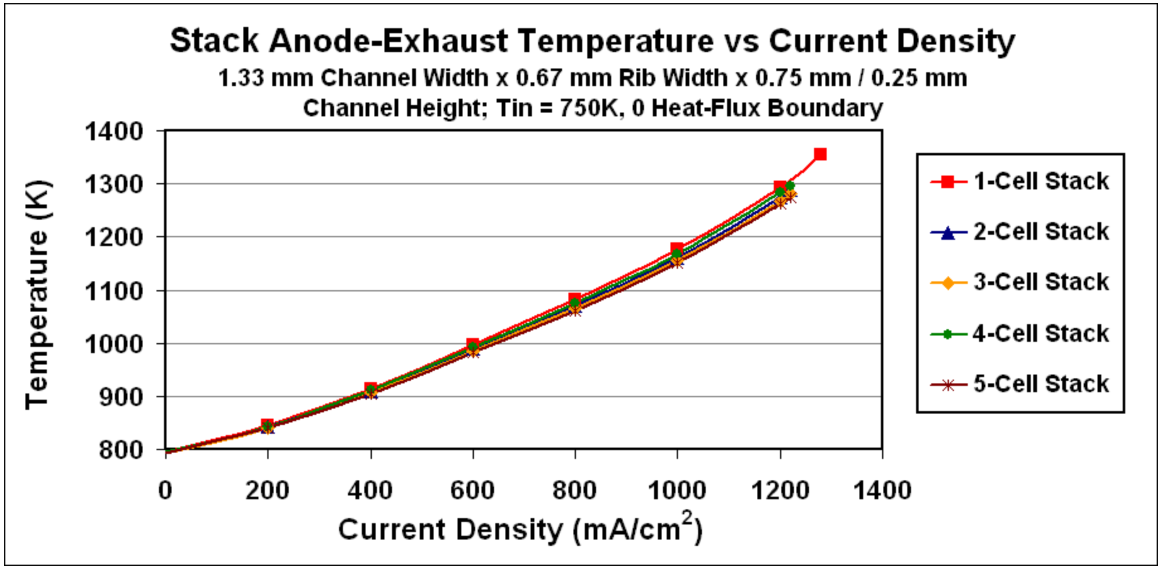
# Fuel Cells in Stack	Total Vstack	V_{Avg} per # Fuel Cells in Stack	ΔV_{Avg} per # Fuel Cells in Stack	Δ%
	V	V	V	%
1	0.5024	0.5024	-	-
2	1.0113	0.5057	0.0033	0.647%
3	1.5199	0.5066	0.0010	0.190%
4	2.0284	0.5071	0.0005	0.093%
5	2.5369	0.5074	0.0003	0.055%
6	3.0454	0.5076	0.0002	0.037%



- ➢ As the number of fuel cells in a stack was increased, the change in the average voltage produced by each individual cell when another cell was added to the stack was reduced and approached zero.

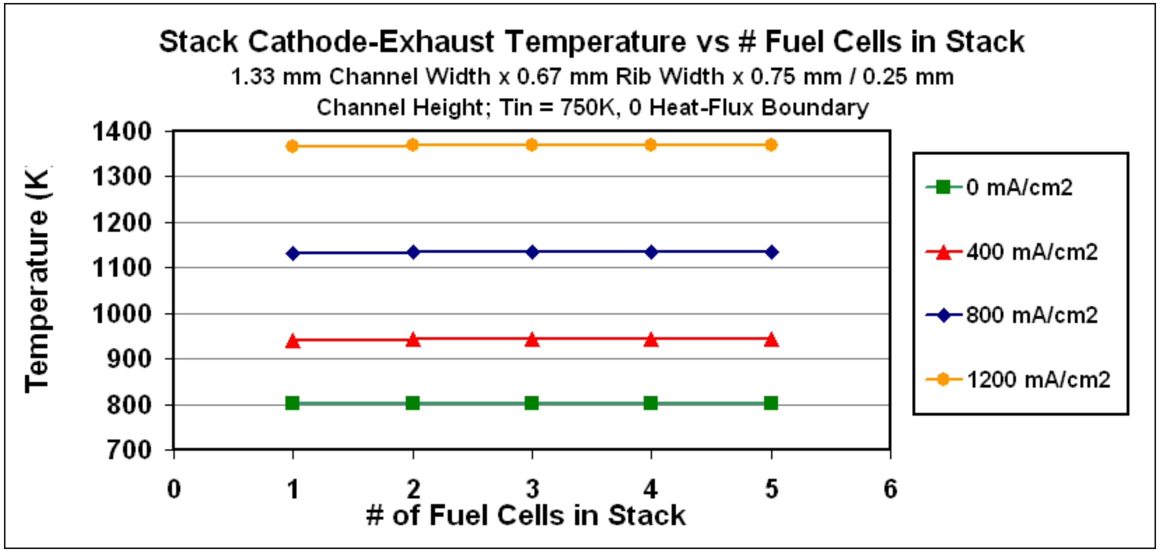
SOFC MULTI-CELL ANALYSES – EXHAUST TEMPERATURE

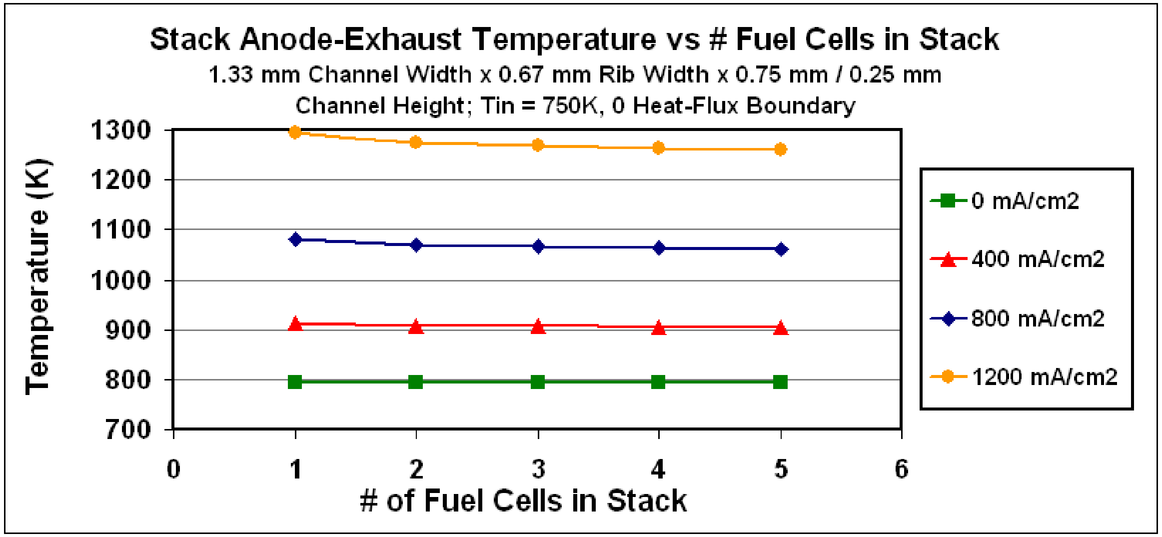




- ➢ The cathode-exhaust temperatures were typically higher than the anode-exhaust temperatures.
- ➢ The overall cathode-exhaust temperature increased very slightly as the number of cells in the stack was increased.
- ➢ The overall anode-exhaust temperature dropped as more cells were added to the stack.
- ➢ This difference in behavior was due, in part, to the significantly large air/fuel ratio (approximately 48) and the resulting cooing effect that the incoming air entering the cathode-flow channels in one cell had on the outgoing exhaust gas leaving the anode-flow passages in the cell above it.

SOFC MULTI-CELL ANALYSES – EXHAUST TEMPERATURE





THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

SOFC MULTI-CELL ANALYSES – EXHAUST TEMPERATURE

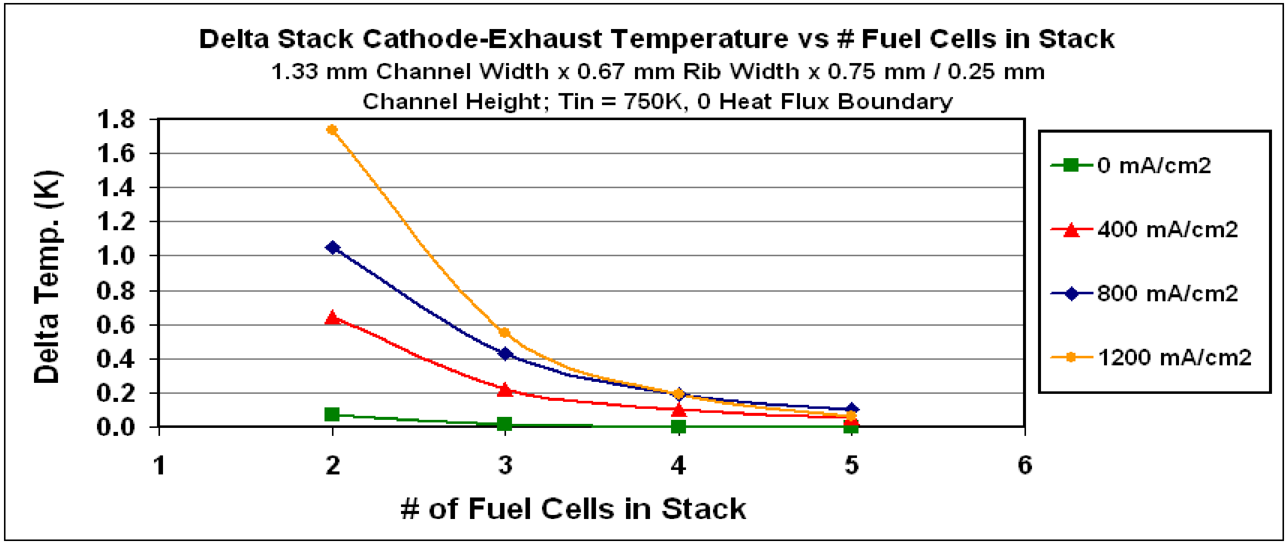
Cathode-Exhaust Temperatures vs. # of Fuel Cells in SOFC Stack
Current Density = 1200 mA/cm^2

# Fuel Cells in SOFC Stack	Cell #1 Tcathex	Cell #2 Tcathex	Cell #3 Tcathex	Cell #4 Tcathex	Cell #5 Tcathex	Cell #6 Tcathex	Overall Stack Tcathex	ΔTcathex	Δ%
	K	K	K	K	K	K	K	K	%
1	1364.1	N/A	N/A	N/A	N/A	N/A	1364.1	-	N/A
2	1356.5	1375.2	N/A	N/A	N/A	N/A	1365.8	1.7	0.13%
3	1355.1	1363.2	1380.9	N/A	N/A	N/A	1366.4	0.6	0.04%
4	1354.2	1360.6	1367.1	1384.5	N/A	N/A	1366.6	0.2	0.01%
5	1353.5	1359.3	1363.9	1369.7	1386.9	N/A	1366.7	0.1	0.01%
6	1352.9	1358.5	1362.3	1366.1	1371.6	1388.7	1366.7	0.0	0.00%

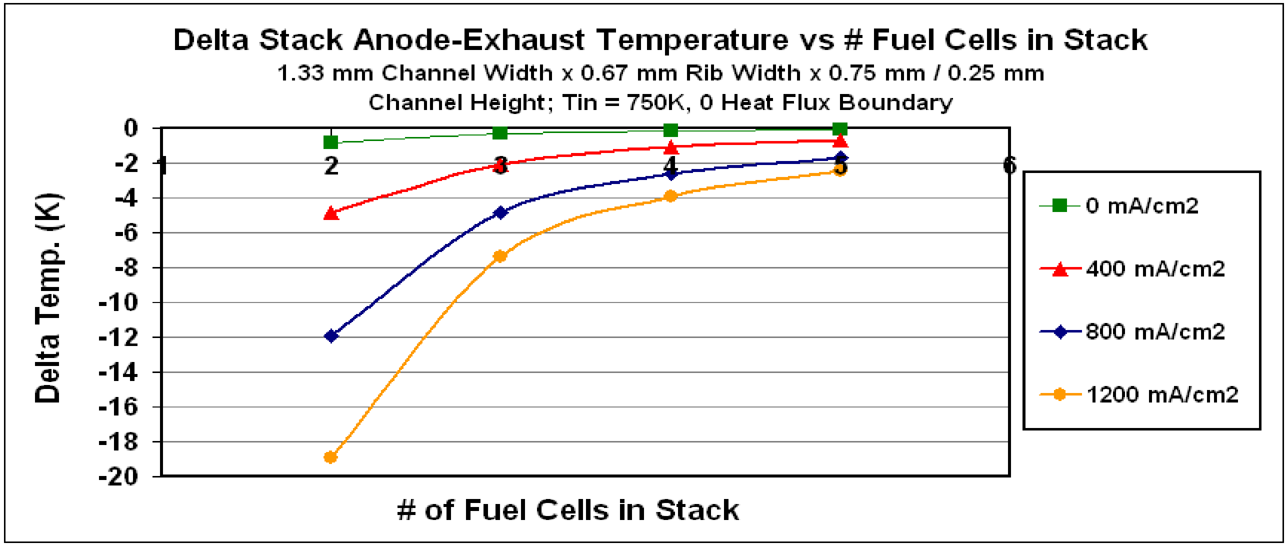
Anode-Exhaust Temperatures vs. # of Fuel Cells in SOFC Stack
Current Density = 1200 mA/cm^2

# Fuel Cells in SOFC Stack	Cell #1 Tanex	Cell #2 Tanex	Cell #3 Tanex	Cell #4 Tanex	Cell #5 Tanex	Cell #6 Tanex	Overall Stack Tanex	ΔTanex	Δ%
	K	K	K	K	K	K	K	K	%
1	1291.1	N/A	N/A	N/A	N/A	N/A	1291.1	-	-
2	1281.9	1262.6	N/A	N/A	N/A	N/A	1272.2	-18.9	-1.46%
3	1279.9	1261.0	1253.7	N/A	N/A	N/A	1264.9	-7.4	-0.58%
4	1279.7	1260.9	1254.2	1249.1	N/A	N/A	1261.0	-3.9	-0.31%
5	1280.0	1261.3	1254.7	1250.5	1246.3	N/A	1258.5	-2.4	-0.19%
6	1280.4	1261.7	1255.3	1251.3	1248.1	1244.4	1256.9	-1.7	-0.13%

SOFC MULTI-CELL ANALYSES –EXHAUST TEMPERATURE



Delta Stack Cathode-Exhaust Temperature vs # Fuel Cells in Stack
1.33 mm Channel Width x 0.67 mm Rib Width x 0.75 mm / 0.25 mm Channel Height; Tin = 750K, 0 Heat Flux Boundary

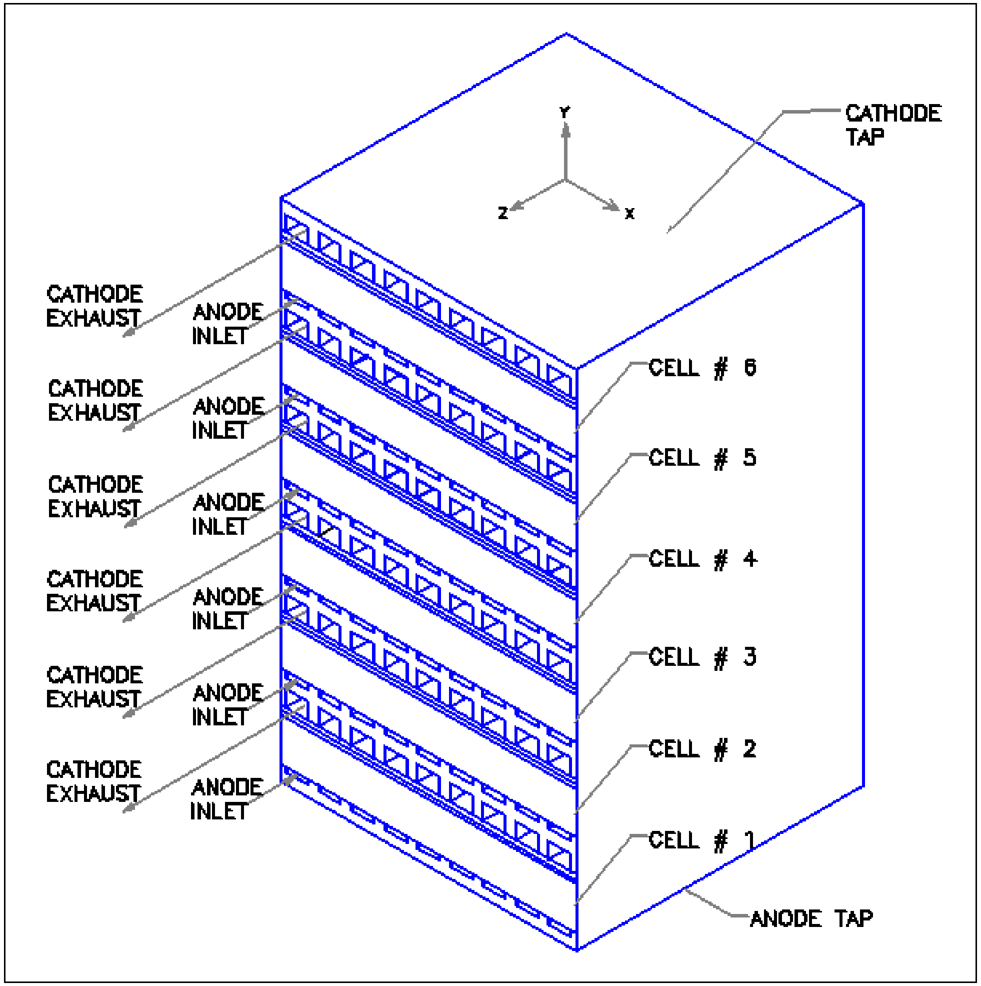


Delta Stack Anode-Exhaust Temperature vs # Fuel Cells in Stack
1.33 mm Channel Width x 0.67 mm Rib Width x 0.75 mm / 0.25 mm Channel Height; Tin = 750K, 0 Heat Flux Boundary

- As the number of fuel cells in a stack was increased, the incremental effect of each additional cell was reduced and the changes in the both the overall cathode-exhaust temperature and the overall anode-exhaust temperature both approached zero.

SOFC MULTI-CELL ANALYSES – 6-CELL STACK

EXHAUST TEMPERATURE VARIATIONS



6-Cell SOFC Stack

- For the 6-cell stack, the highest cathode-exhaust gas temperature was at the outlet from cell # 6 at the top of the stack.

- The lowest cathode-exhaust temperature was at the outlet from cell #1 located at the bottom of the stack.

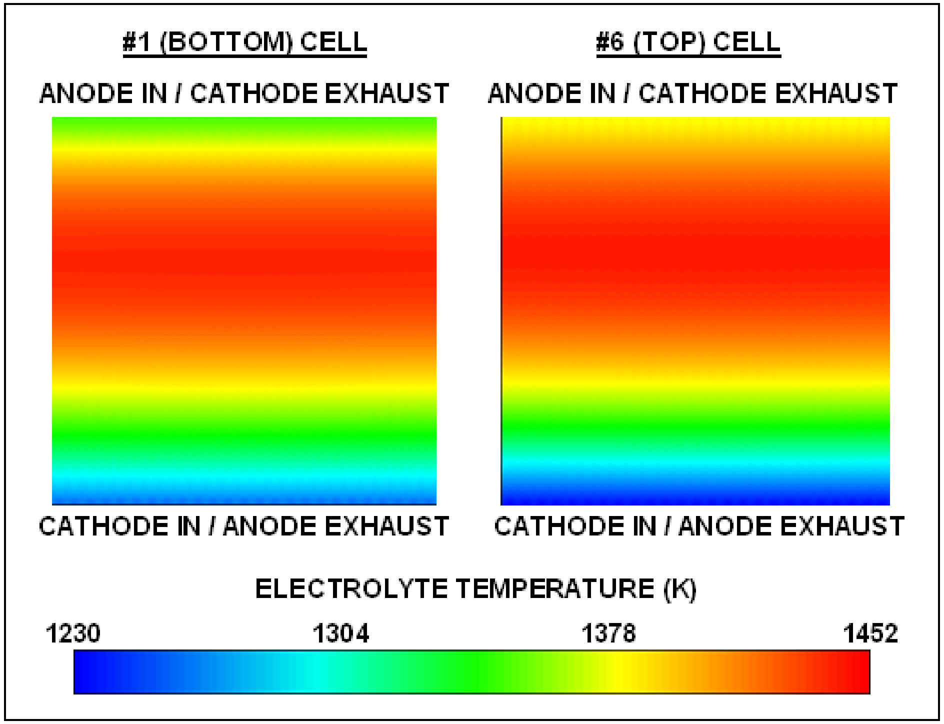
- This temperature difference was due to the effect of the insulated cathode tap that is adjacent to the top of the cathode-flow channels in cell # 6 and reduced the heat transferred from the gas in these channels.

- In cell #1, however, the upper surfaces of the cathode-flow channels are adjacent to the lower surfaces of the anode-flow channels in cell #2. Consequently, the cathode-exhaust gas leaving cell #1 gave up heat to the relatively cold fuel entering cell #2.

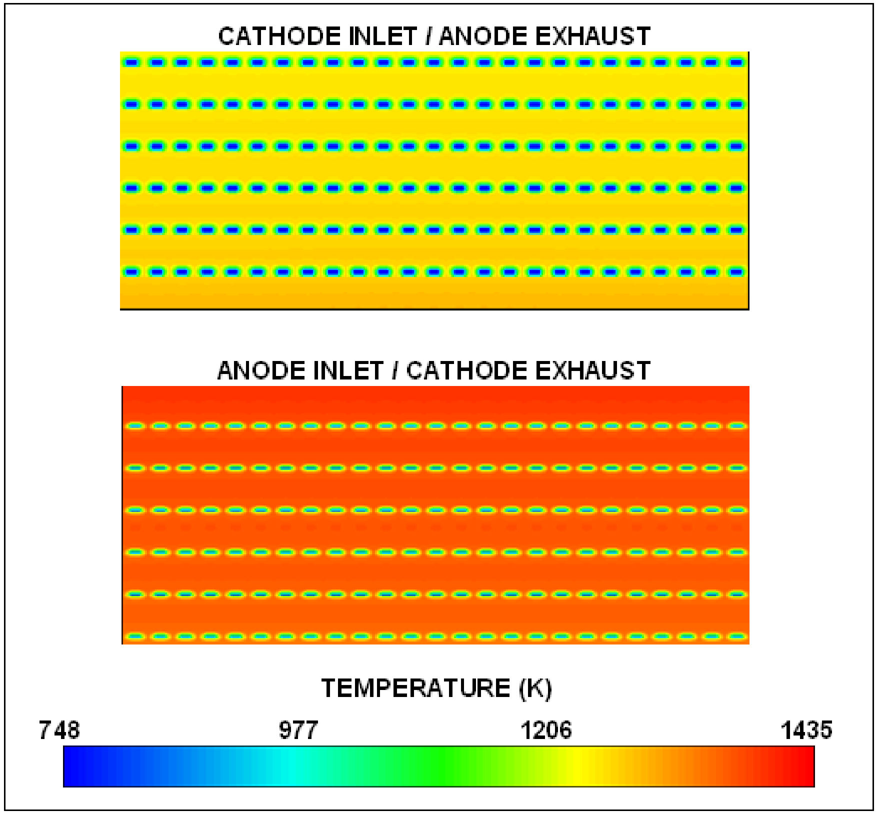
- The opposite effect occurred in the anode-flow channels, and the hottest anode-exhaust gas was at the outlet from cell #1 while the lowest anode-exhaust temperature was at the outlet from cell #6.

SOFC MULTI-CELL ANALYSES – 6-CELL STACK

EXHAUST TEMPERATURE VARIATIONS

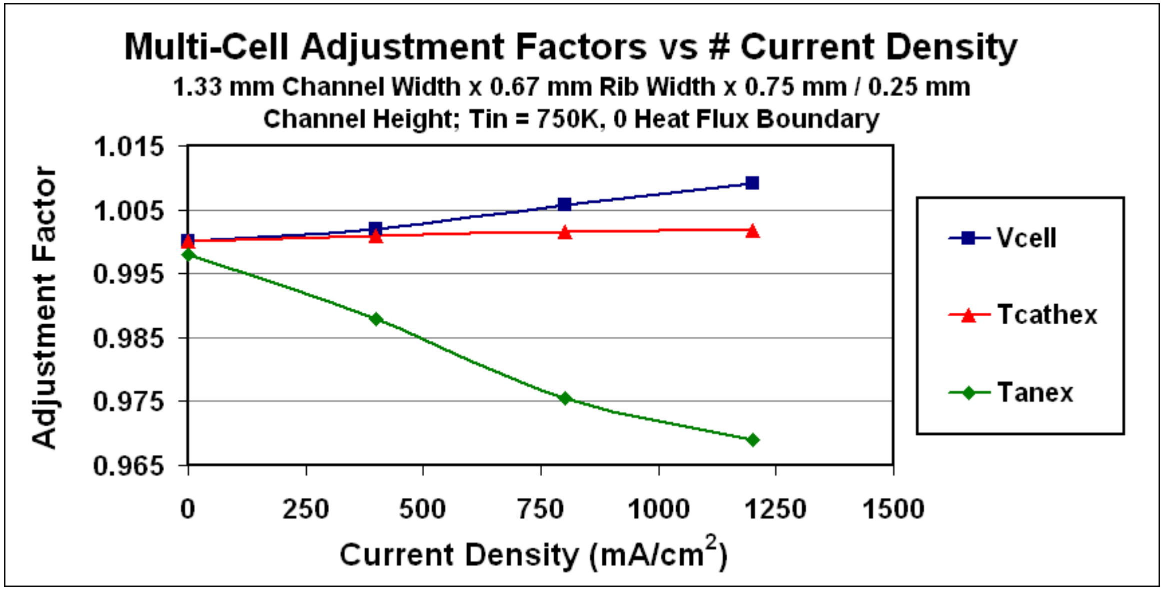


#1 and #6 Electrolyte Temperature Distribution in 6-Cell SOFC Stack



Temperature Distribution @ Inlet & Outlet of 6-Cell SOFC Normal to Flow Direction

MULTI-CELL ADJUSTMENT FACTORS



- ➢ Multi-cell CFD results were extrapolated to develop estimates of the changes in the average voltage produced per cell in a stack and in the overall cathode- and anode-exhaust temperatures when the number of fuel cells in a stack exceeded six.

- ➢ It was found that after the number of fuel cells in a stack reached approximately 50, the changes in the average voltage per cell and in the overall cathode- and anode-exhaust temperatures converged to zero.

- ➢ Based on this, the total differences in the average voltage per cell and in the overall cathode- and anode-exhaust temperatures between single fuel-cell values and the converged values for the 50-cell stack were determined, and adjustment factors that could enable single-cell CFD results to be modified to reflect multi-cell performance were developed.

- ➢ This process was repeated for various current-density values.

CONCLUSIONS OF MULTI-CELL STUDY

- A process was followed in which five SOFC stacks, together with a single-cell SOFC, were analyzed using CFD.
- A comparison of the results of these analyses enabled adjustment factors to be developed that can be used to develop an estimate of the voltage produced by a multi-cell SOFC stack based on the results of a single-cell CFD analysis.
- Adjustment factors were also developed for the cathode-exhaust and anode-exhaust temperatures.
- This process could significantly reduce both the time and the computing resources necessary to complete a preliminary SOFC design.

Marine Fuel Cell Use

- Military Vessels
- Small Boats, Water-Taxies & Ferries
- Commercial Marine Vessels

Military-Vessel Fuel-Cell Applications

PROJECT	DATE	STATUS	FC TYPE	KW	FUEL	VESSEL	FC DEVELOPER (Model)
Attack Submarines with FC Air Independent Propulsion (AIP) by Howaldtswerke-Deutsche Werft GmbH (HDW) and other S/Ys for German Navy and for Export	1980s	Test Unit	AFC			Class 205 Submarine U1	
	1995 to 2013	1st Sub launched March 2002	(9) PEMFC per Vessel	34 ea	Hydrogen w/ metal hydride storage	(8) Class 212 A Submarines	Seimens AG (SINAVY$^{\text{CIS}}$ BZM 34)
	2000 to 2009	1st Sub launched April 2004	(2) PEMFC per Vessel	120 ea.		(7) Class 214 Submarines	Seimens AG (SINAVY$^{\text{CIS}}$ BZM 120)
	2004 to 2010	Ongoing				(2) Class 209 PN Submarines	
	2002 to 2010	Ongoing	PEMFC			(3) Class 209 Submarine Modernizations	
	2006 to 2012	Ongoing	PEMFC			(2) Dolphin Class Submarines	
Canadian Submarine w/ AIP	FC design started 1994	Test model 1999; no installations	PEMFC	250	Methanol	(4) *Victoria* Class SSKs	Ballard Power Systems
Spanish Submarine w/ AIP	Started July 2006	Ongoing	PEMFC	300	Reformed Ethanol	S-80 Submarine	UTC Power
Russian Submarines w/ AIP	Started late 1980s	Lab test 1991		130	Hydrogen	Pirahnya-Class Midget Submarines	SKBK Special Boiler Design Bureau (Kristall-20 AIP)
	Design started around 1998	Intended for installation during vessel construction or modification			Hydrogen w/ intermetallid storage	Amur-Class Submarines	SKBK (Kristall-27E AIP)
Italian/Russian Submarine w/ AIP	Joint Venture started around 2004	Mock-up model at EURONAVAL 2006				S1000 Submarine	
U.S. Coast Guard	1995 to 1998	Conceptual Design	(4) MCFC per Vessel	625 ea	Navy Distillate Fuel (F-76)	USCGC *VINDICATOR*	Energy Research Corporation

Military-Vessel Fuel-Cell Applications (contd.)

PROJECT	DATE	STATUS	FC TYPE	KW	FUEL	VESSEL	FC DEVELOPER (Model)
European Naval Frigate	2000 to 2005	Conceptual Design	PEMFC	500	Navy Distillate Fuel (F-76)	Ship's Service Fuel Cell - Naval Frigates	
Studies by Arctic Energy Ltd.	1987	U.S. Navy Ship of the Future Study	Various	100	Various	Large Naval Combatant Ship	
	1989	U.S. Navy R&D	Various	50	Various	Small Submersibles	
	1994	NOAA Study	(12) MCFC	180 ea.	Diesel Oil	TAGOS Vessel	
Office of Naval Research Enabling Technologies Project	1993	Ship Impact Study	PEMFC, MCFC, PAFC, SOFC		Various	Naval Destroyer & Corvette	
U.S. Navy Ship Service Fuel Cell (SSFC) Program	Phase 1: 1997 to 1999	Conceptual Design	(4) MCFC	650 ea.	Navy Distillate Fuel (F-76)	Various Surface Vessels	Energy Research Corporation
			PEMFC	2500			Ballard / McDermott
		Lab Demonstration	PEMFC	Apx. 2	Hydrogen		Ballard Power Systems
			Fuel Processor	20	Navy Distillate Fuel (F-76)		McDermott Technology, Inc.
	Phase 2: 2000 to 2008	Demo Integrated Fuel Processor (IFP) Unit Lab Tested 2004	IFP for PEMFC	500	Navy Distillate Fuel (F-76)		McDermott Technology, Inc.
		1st Generation FC Demo Unit being Lab Tested	MCFC	625	Logistics Fuel (JP-5, JP-8, F-76, MGO)		Fuel Cell Energy, Inc.
U.S. Navy Advanced Fuel Cell Program	2008 to 2010	2nd Generation FC System	PEMFC & SOFC				
Palmer-Kumar Combined Cycle	2006	Conceptual Design	SOFC	20,000	Methane	Nuclear Aircraft Carrier	

Small Boat, Water-Taxi, & Ferry Fuel-Cell Applications

PROJECT	DATE	STATUS	FC TYPE	KW	FUEL	VESSEL	FC DEVELOPER (Model)
ICEU Passenger Boat	1999	Planned as EXPO 2000 Project	PEMFC	10	Hydrogen in metal hydride	MS *Weltfrieden*	
etaing GmbH Passenger Boat	built in 2000	First operated June 2000 in Bonn then moved to Leipzig	AFC	6.9	Hydrogen in metal hydride	39-ft, 22-Passenger Boat the *Hydra*	ZeTek (Europ 21)
EIVD, Switzerland	1998	Small leisure boats built	PEMFC	0.1	Compressed Hydrogen	*Hydroxy 100*	Paul Scherrer Institute
				0.3		*Hydroxy 300*	
	2003			3		*Hydroxy 3000*	
Ansaldo Richerche	1998	Tested on Lago Maggiore, Italy	PEMFC	40	Gasified liquid hydrogen	90-Passenger Boat	Nuvera Fuel Cells
Duffy-Herreshoff Water Taxi	2002 to 2003	Tested in Newport Beach, CA, 2003	(4) PEMFC	1.5 ea.	Millenium Cell Hydrogen on Demand^{TM} (sodium borohydride)	30-ft, 18-Passenger Water Taxi	Anuvu, Inc. (Power-X^{TM})
San Francisco WTA Commuter Ferry	Design Started 2002	Pending	(2) PEMFC	120 ea.	Hydrogen in metal hydride	24-m, 49-Passenger Treasure-Island Ferry	Anuva, Inc. or UTC Power
Pearl Harbor USS Arizona Memorial Shuttle	Initial Funds Obligated Sept. 2003			75	Compressed Hydrogen	149-Passenger Launch	
Sailing Yacht	2005	Trials during 2005	PEMFC	10	Hydrogen by electrolysis (powered by wind turbine & propeller) stored in metal hydride	HaveBlue *XV1* 42-ft MKII Sailboat	Hydrogenics (HyPM)
Sailing Yacht	2005		DMFC	0.05	Methanol	SY *Mamelie*	Max Power / Smart Fuel Cell (MFC AHD-100)
DCH Water Taxi	2001	Demo San Francisco, CA, Oct. 2001	PEMFC	1	Compressed Hydrogen	18-ft, 9-Passenger Water Taxi	DCH Technologies, Inc. / Enable^{TM} Fuel Cell Corp.

Small Boat, Water-Taxi, & Ferry Fuel-Cell Applications (contd.)

PROJECT	DATE	STATUS	FC TYPE	KW	FUEL	VESSEL	FC DEVELOPER (Model)
Prototype Yacht	2003 to 2005	Demo on Lake Constance, Germany, Oct. 2003	PEMFC	4.8	Hydrogen	12-m Yacht *No. 1*	MTU-Friedrichshafen ("Cool Cell") / Ballard Power Systems
EC / German-Czech ZEM/SHIPS	Started Nov. 2006	In service on Alster lake, Hamburg, Aug. 2008	(2) PEMFC	48 ea.	Hydrogen	25.6-m, 100-Passenger Vessel FCS *Alsterwasser*	Proton Motor Fuel Cell GmbH (PM 600)
H2Yacht GmbH	Started in 2004	Prototype launched in Elbe River 2005	PEMFC	1.2	Compressed Hydrogen	5.8-m, 6-Person Motorboat	Ballard Power Systems (Nexa® Power Module)
		Exhibited at H2Expo 2006	(2) PEMFC	1.4 ea.		6.75-m, 8-Person Motorboat	
Ecofys & Dutch Knowledge Ctr. For Yachbuilding	Launched Summer 2006	Introduced during Frisian Nuon Solar Challenge	PEMFC		Compressed Hydrogen in canisters	Sloop *Xperiance*	
Fuel Cell Boat BV H-ferry Project	2007-2008		PEMFC	60 to 70	Compressed Hydrogen	24-m, 100-Passenger Amsterdam River IJ Ferry	
Iceland SMART-H2 (APU)	Test planned June 2008		PEMFC	10 to 15	Hydrogen	150-Passenger Whale-Watching Ship *Elding*	Ballard Power Systems
Beneteau Oceanis Clipper 411 (APU)	FC installed mid-2007	Tested during 2007 Atlantic Rally for Crusiers		1	LPG	41-ft sailing yacht *Emerald*	Voller Energy Group (Emerald)
University of Birmingham [50]	Launched Sept. 2007	Protium Project	PEMFC	5	Hydrogen in metal hydride	12-ton Canal Boat *Ross Barlow*	EMPA Laboratories
Shanghai Maritime University	Tested in 2005	Displayed at 6th Int'l. Industry Exhibition in Shanghai, 2005	PEMFC	2	Hydrogen	4.8-m, 2-Passenger Boat	
Brunnert-Grimm AG Runabout	Deliveries planned 2008	Displayed at INTERBOOT 2007			Compressed Hydrogen	Cobolt 233 ZET	zebotec GmbH

COMMERCIAL MARINE FUEL-CELL APPLICATIONS

PROJECT	DATE	STATUS	FC TYPE	KW	FUEL	VESSEL	FC DEVELOPER (Model)
Arctic Energy Ltd.	1984	Study for U.S. Maritime Administration	PAFC	30 to 60	Methanol	Surface Ship Auxiliary Power / Training Ship	
U.S. Maritime Administration	1998	Study	MCFC	3000	Compressed Natural Gas	Container Ship	
EU / FC-SHIP Conceptual Design	July 2002 to July 2004	Final Report issued July 2004	PEMFC	2000	Liquid Hydrogen	140-m RO/RO Fast Ferry (Auxiliary Power)	
			MCFC, SOFC		Low sulfur diesel, LNG		
			PEMFC	400	Compressed Hydrogen Gas	30-m Habor Ferry (Propulsion)	
DNV / Eureka - Fellow SHIP	2003 to 2005	Feasability Study	SOFC / MCFC				
	Phase 1: 2003 to 2006	Demonstrated at exhibitions 2006	PEMFC		Hydrogen	*Viking Fellowship* 1:84 Scale Model	
	Phase 2: Ongoing	Ship testing started Dec. 2009	MCFC	320	LNG	Eidesvik Offshore OSV M/V *Viking Lady* (Auxiliary Power)	MTU CFC Solutions GmbH (HotModule)
	Phase 3: Ongoing	Ship installation planned	(4) Hybrid w/ steam turbine	1000 ea.		Eidesvik Offshore OSV (Propulsion)	
EU / METHAPU	2007 to 2010	Lab test started Oct. 2007, Ship installation May 2010	SOFC	20	Renewable Methanol	Wallenius Marine Car Carrier M/V *Undine*	Wärtsilä Corp. (WFC20α)
		Design Study		250			Wärtsilä Corp.
EU / NEW H-SHIP	2004 to 2005	Identify barriers to H_2 on ships			Hydrogen	Icelandic Fishing Vessels	
EU / MC-WAP	2005 to 2010	Study of MCFC on ships, APU test planned	MCFC	500	Diesel oil	RO/RO, RO-PAX, Cruise, Fast Ships	Ansaldo Fuel Cells
Wallenius Marine	Scale Model Planned 2005	Concept ship for 2025			Hydrogen from solar, wind and wave power	E/S *Orcelle* 250-m 10,000-car RO/RO	
Offshore Ship Designers Group "Green Tug"	Design Started 2008	1st Tug Planned for 2010	(2) PEMFC	100 kW ea.	Compressed Hydrogen	Hydrogen Hybrid Harbor Tug (HHHT)	NedStack fuel cell Technology BV (PS100)

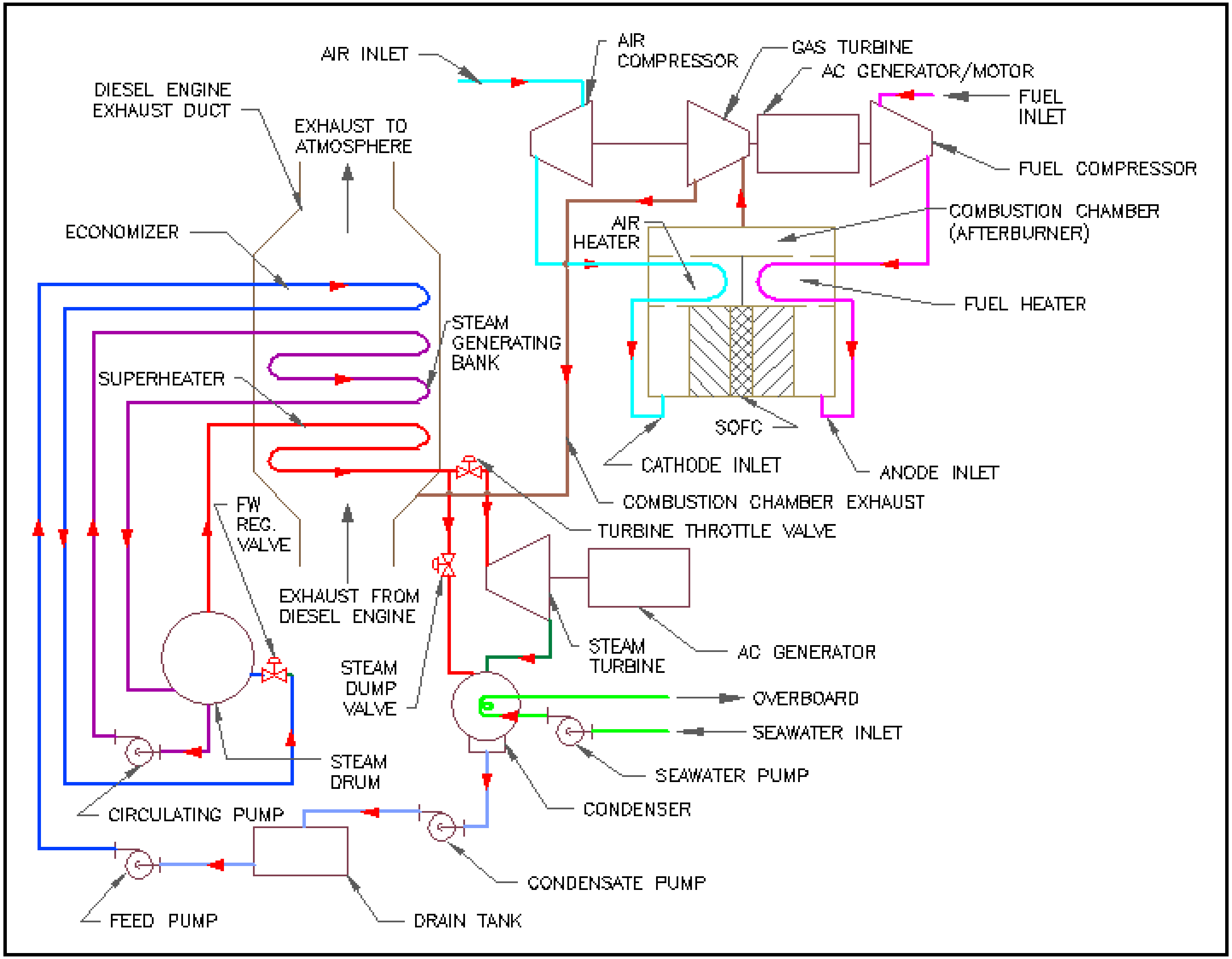
ANALYSES OF SOFC HYBRID SYSTEM TO GENERATE SHIPBOARD ELECTRICAL POWER

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

Large Marine Propulsion Diesel Engine
(Courtesy of Wärtsilä Corp.)

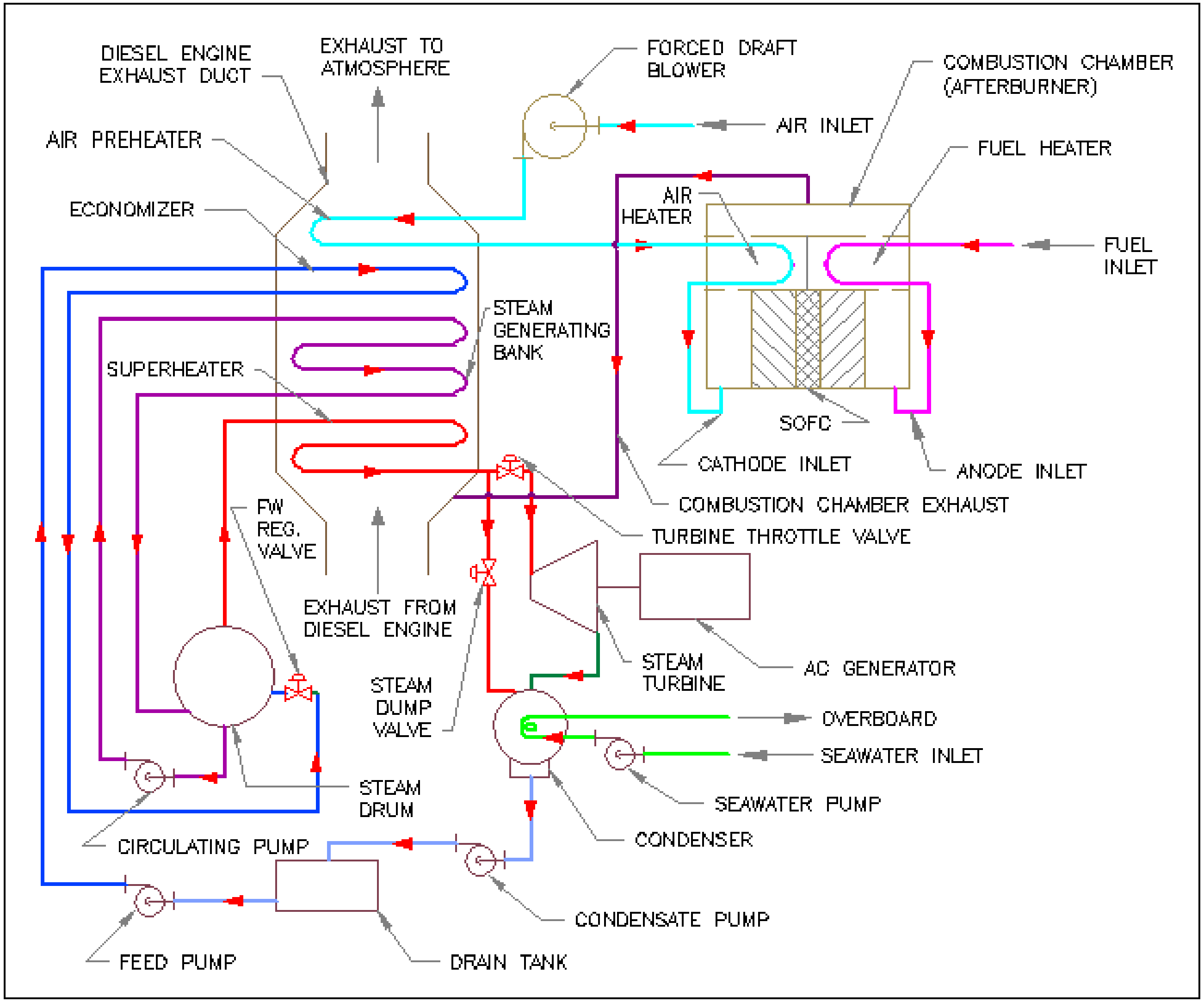
OVER 85,000 COMMERCIAL-MARINE VESSELS
99% POWERED BY DIESEL ENGINES

FUEL-CELL GT/ST-1P HYBRID SYSTEM



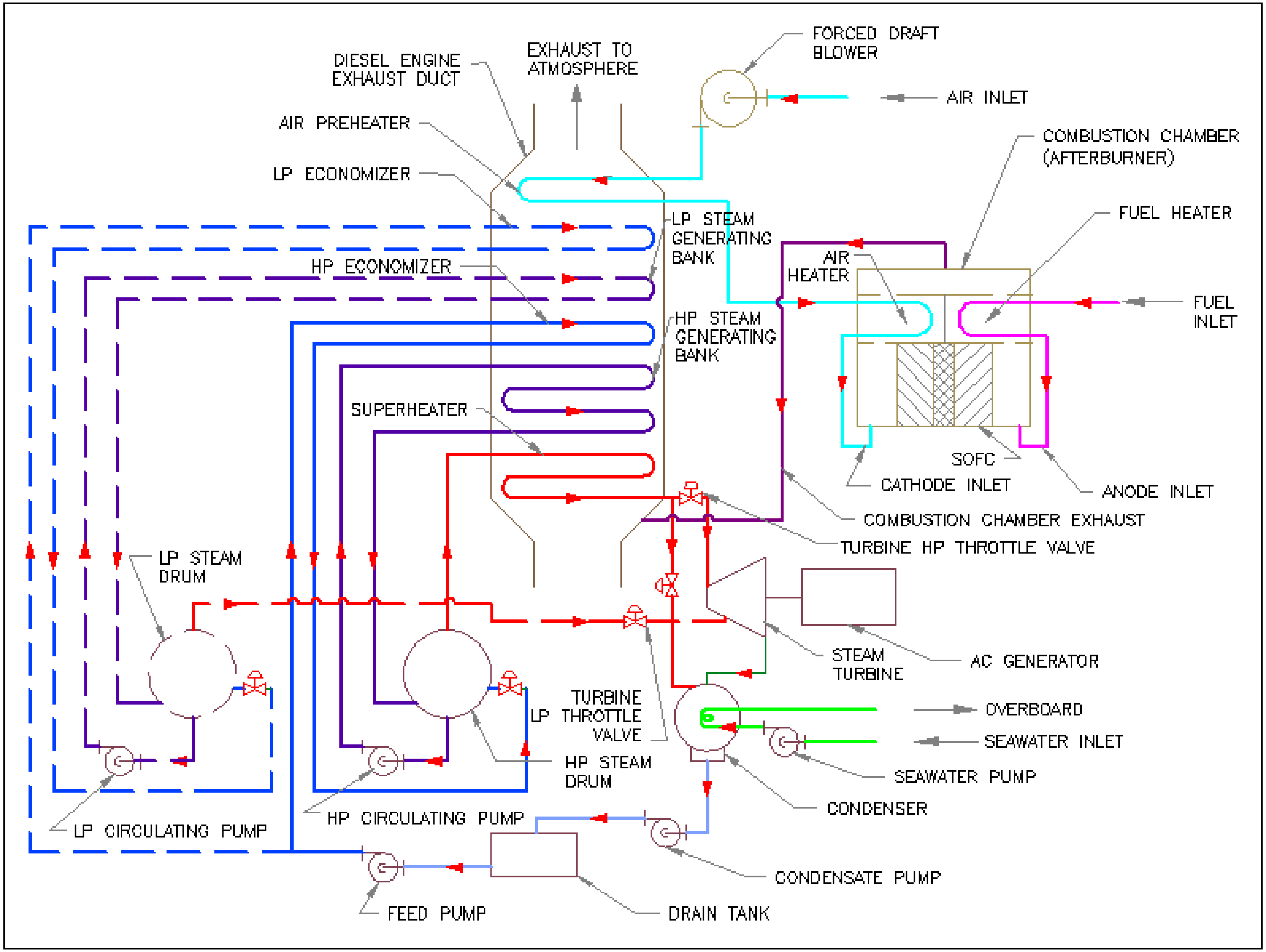
THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

FUEL-CELL ST-1P HYBRID SYSTEM



THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

FUEL-CELL ST-2P HYBRID SYSTEM



SOFC HYBRID SYSTEM ANALYSES CONDITIONS

- **Four Hybrid cycles evaluated: SOFC w/Single-Pressure Steam Turbine (ST-1P), SOFC w/Dual-Pressure Steam Turbine(ST-2P), SOFC w/Gas Turbine & Single-Pressure Steam Turbine (GT-1P), and SOFC w/Gas Turbine & Dual-Pressure Steam Turbine (GT-2P).**

- **Four Steam Pressures Considered: 45 bar, 30 bar, 15 bar, and 7.5 bar**

- **Two Condensing Pressures Considered: 0.05 bar and atmospheric pressure**

- **Values of current were varied from 5 A to 30 A.**

- **Turbogenerator and auxiliary efficiencies determined based on SNAME guidelines**

- **The minimum pinch point used between the SOFC-exhaust gas and the steam or feedwater temperatures was set at 15 °K.**

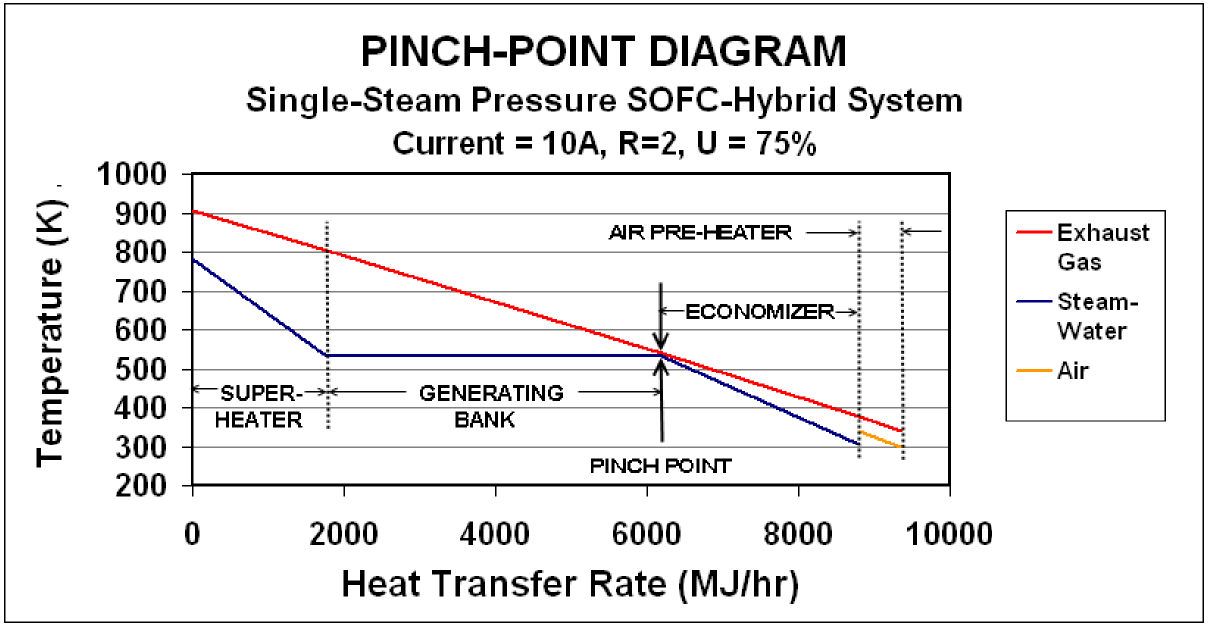
- **The total net power produced by each system was set at 4000 kW (Based on a typical container ship requirement), and the output voltage from the system was set at 440 V.**

SOFC HYBRID SYSTEM ANALYSES CONDITIONS (contd.)

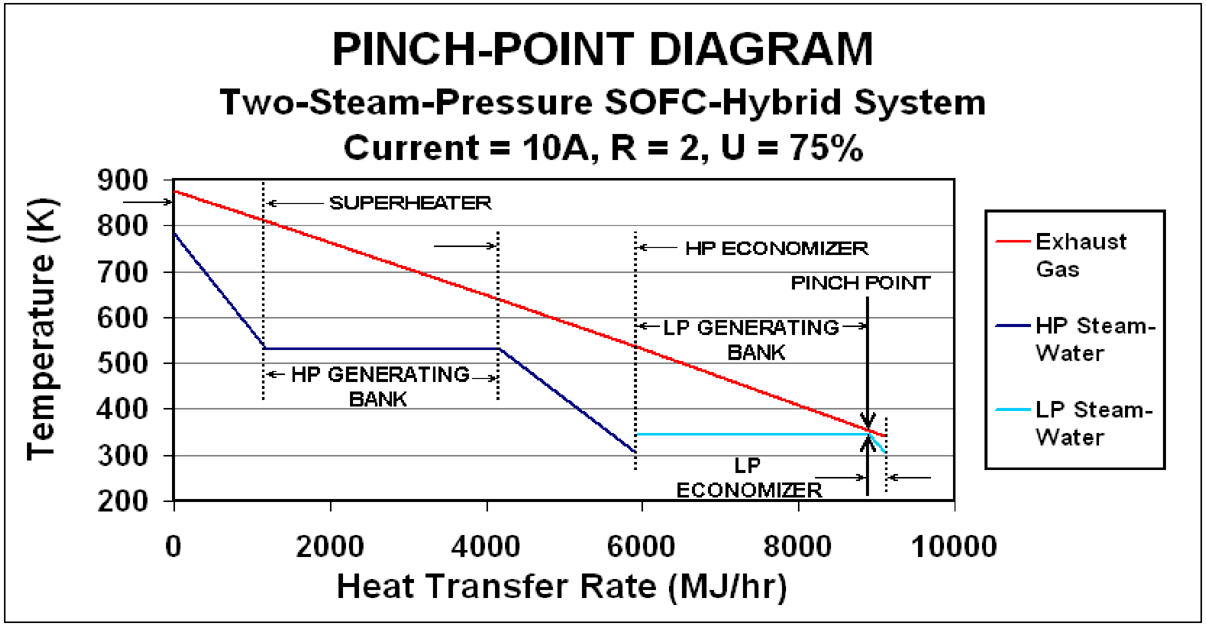
- For many of the analyses conducted, the fuel was assumed to be composed of 100% hydrogen. However, methane (CH4) and methanol (CH3OH) were also used in some of the analyses.
- Oxygen supplied to the cathode as a component in air at a temperature of 298 °K with 40% relative humidity.
- The air ratio used ranged from 1.5 to 4 and the fuel utilization factor was varied from 90% to 55%
- The SOFC was assumed to be operating at full load under steady-state conditions; partial-load conditions or transient loads were not considered.
- The maximum steam temperature at the superheater outlet was limited to 783 °K (950 °F).
- The efficiency of the inverter required to convert the direct current produced by the SOFC to alternating current was assumed to equal 95%.
- Overall cycle efficiencies were based on fuel lower-heating values (LHV).

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

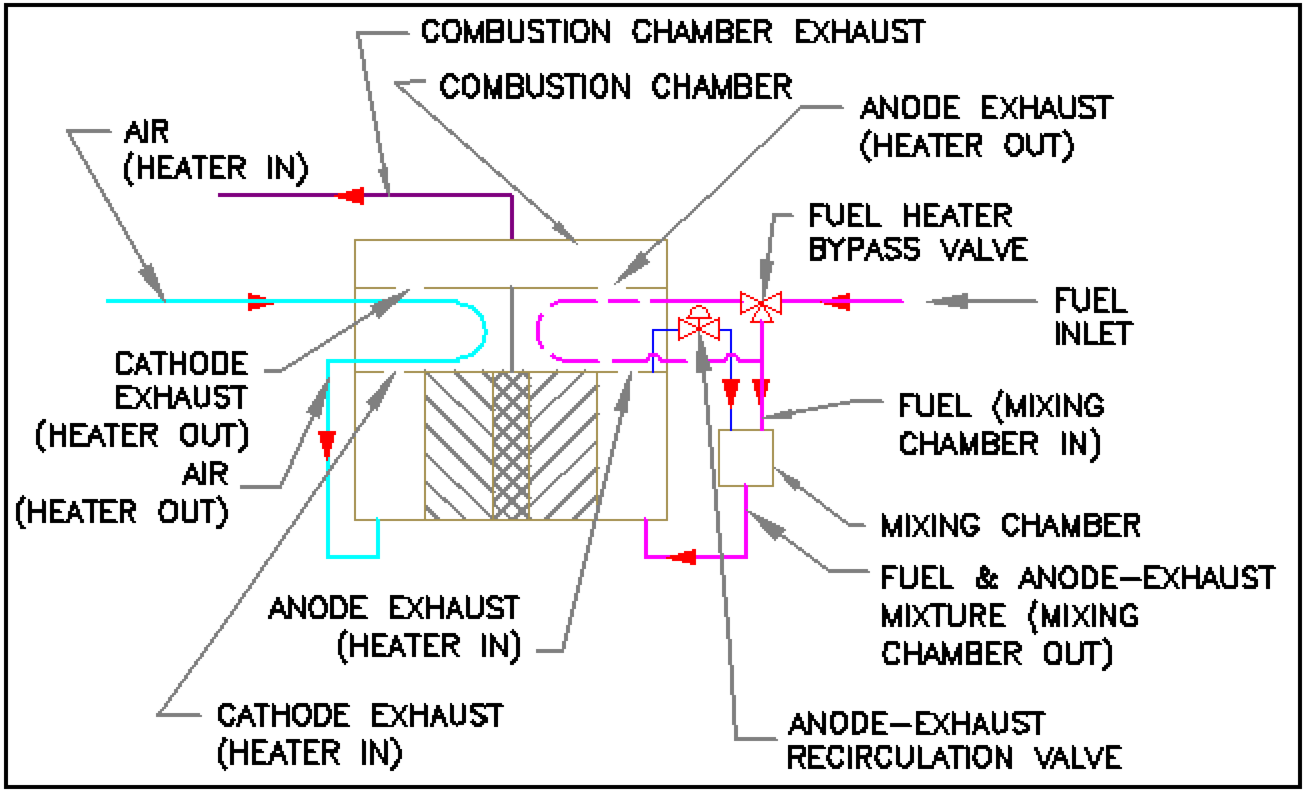
Single-Steam Pressure System Pinch-Point Diagram



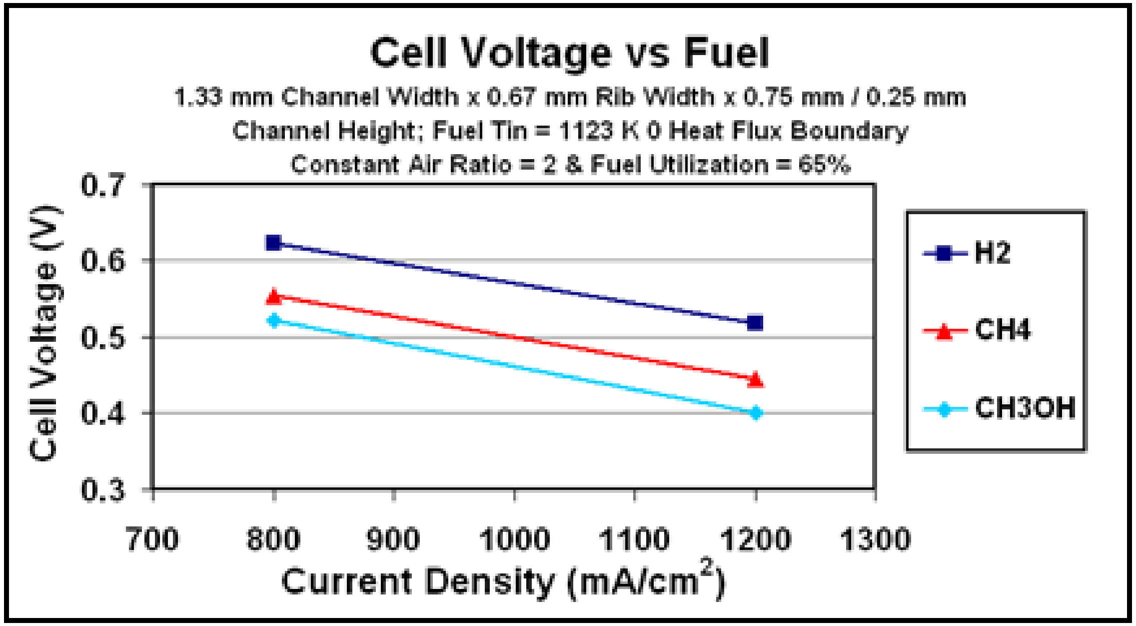
Dual-Steam Pressure System Pinch-Point Diagram



ALTERNATE-FUEL DIRECT-INTERNAL REFORMING (DIR)



ALTERNATE-FUEL PERFORMANCE



Reactions occurring during DIR of Methane:

Steam Reforming: $CH_4 + H_2O = 3H_2 + CO$

Water-Gas Shift: $CO + H_2O = H_2 + CO_2$

Reactions occurring during DIR of Methanol:

Steam Reforming: $CH_3OH + H_2O = 3H_2 + CO_2$

Methanol Decomposition: $CH_3OH = 2H_2 + CO$

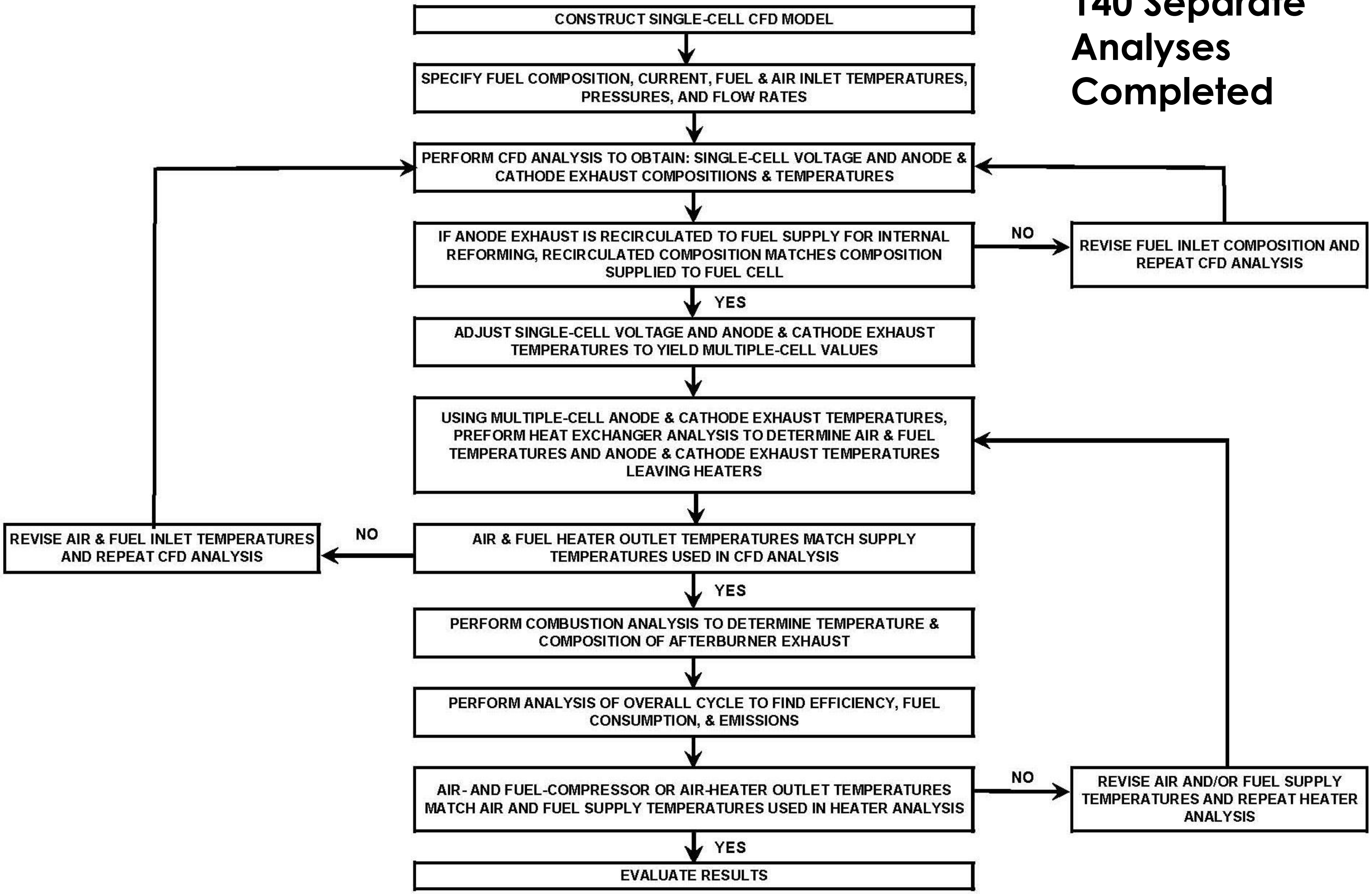
Water-Gas Shift: $CO + H_2O = H_2 + CO_2$

Methanation: $CO + 3H_2 = CH_4 + H_2O$

THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

SOFC/HSRG HYBRID CYCLE ANALYSIS PROCEDURE

140 Separate Analyses Completed



CONSTRUCT SINGLE-CELL CFD MODEL

SPECIFY FUEL COMPOSITION, CURRENT, FUEL & AIR INLET TEMPERATURES, PRESSURES, AND FLOW RATES

PERFORM CFD ANALYSIS TO OBTAIN: SINGLE-CELL VOLTAGE AND ANODE & CATHODE EXHAUST COMPOSITIIONS & TEMPERATURES

IF ANODE EXHAUST IS RECIRCULATED TO FUEL SUPPLY FOR INTERNAL REFORMING, RECIRCULATED COMPOSITION MATCHES COMPOSITION SUPPLIED TO FUEL CELL

NO

REVISE FUEL INLET COMPOSITION AND REPEAT CFD ANALYSIS

YES

ADJUST SINGLE-CELL VOLTAGE AND ANODE & CATHODE EXHAUST TEMPERATURES TO YIELD MULTIPLE-CELL VALUES

USING MULTIPLE-CELL ANODE & CATHODE EXHAUST TEMPERATURES, PREFORM HEAT EXCHANGER ANALYSIS TO DETERMINE AIR & FUEL TEMPERATURES AND ANODE & CATHODE EXHAUST TEMPERATURES LEAVING HEATERS

AIR & FUEL HEATER OUTLET TEMPERATURES MATCH SUPPLY TEMPERATURES USED IN CFD ANALYSIS

NO

REVISE AIR & FUEL INLET TEMPERATURES AND REPEAT CFD ANALYSIS

YES

PERFORM COMBUSTION ANALYSIS TO DETERMINE TEMPERATURE & COMPOSITION OF AFTERBURNER EXHAUST

PERFORM ANALYSIS OF OVERALL CYCLE TO FIND EFFICIENCY, FUEL CONSUMPTION, & EMISSIONS

AIR- AND FUEL-COMPRESSOR OR AIR-HEATER OUTLET TEMPERATURES MATCH AIR AND FUEL SUPPLY TEMPERATURES USED IN HEATER ANALYSIS

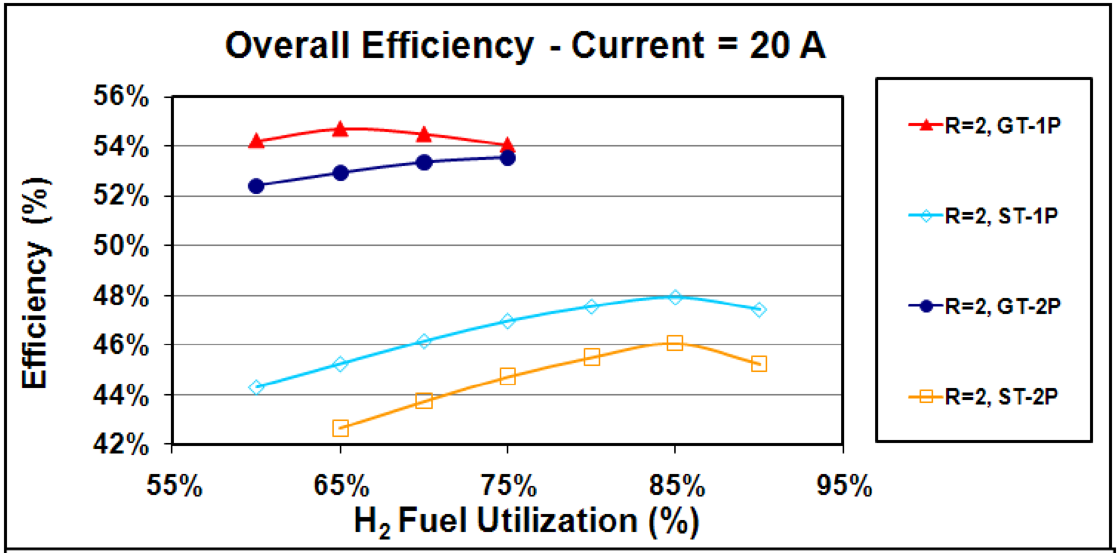
NO

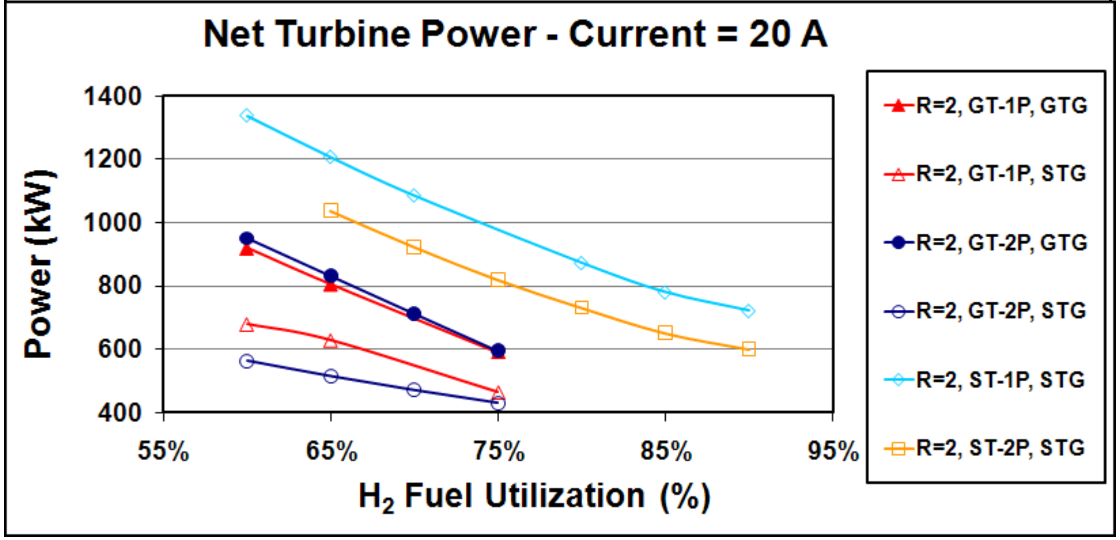
REVISE AIR AND/OR FUEL SUPPLY TEMPERATURES AND REPEAT HEATER ANALYSIS

YES

EVALUATE RESULTS

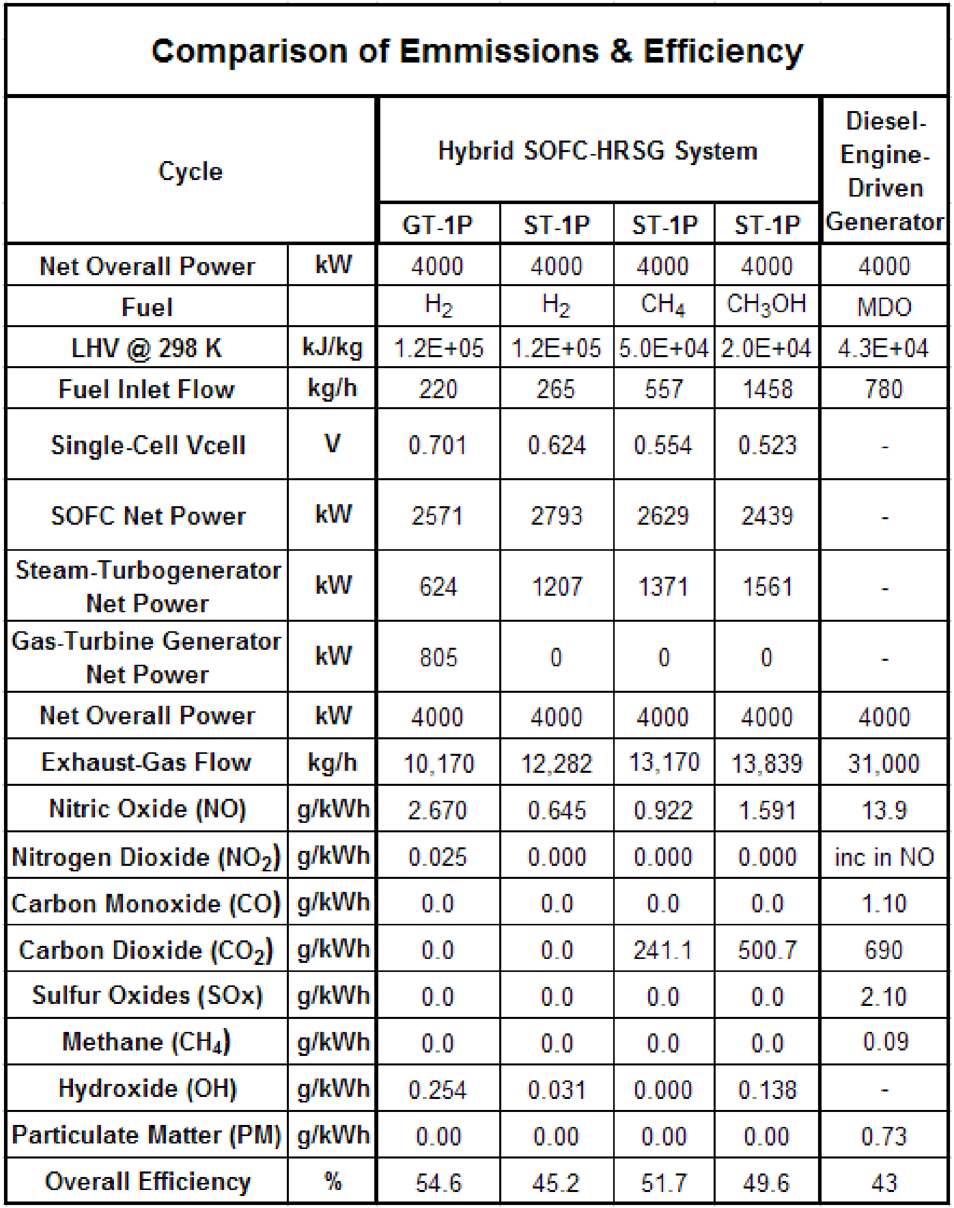
FUEL-CELL HYBRID SYSTEM ANALYSES RESULTS





THE POTENTIAL USE OF FUEL CELLS TO GENERATE SHIPBOARD ELECTRICAL POWER

FUEL-CELL HYBRID SYSTEM EFFICIENCY RESULTS



Comparison of Emmissions & Efficiency

Cycle		Hybrid SOFC-HRSG System				Diesel-Engine-Driven Generator
		GT-1P	ST-1P	ST-1P	ST-1P	
Net Overall Power	kW	4000	4000	4000	4000	4000
Fuel		H_2	H_2	CH_4	CH_3OH	MDO
LHV @ 298 K	kJ/kg	1.2E+05	1.2E+05	5.0E+04	2.0E+04	4.3E+04
Fuel Inlet Flow	kg/h	220	265	557	1458	780
Single-Cell Vcell	V	0.701	0.624	0.554	0.523	-
SOFC Net Power	kW	2571	2793	2629	2439	-
Steam-Turbogenerator Net Power	kW	624	1207	1371	1561	-
Gas-Turbine Generator Net Power	kW	805	0	0	0	-
Net Overall Power	kW	4000	4000	4000	4000	4000
Exhaust-Gas Flow	kg/h	10,170	12,282	13,170	13,839	31,000
Nitric Oxide (NO)	g/kWh	2.670	0.645	0.922	1.591	13.9
Nitrogen Dioxide (NO_2)	g/kWh	0.025	0.000	0.000	0.000	inc in NO
Carbon Monoxide (CO)	g/kWh	0.0	0.0	0.0	0.0	1.10
Carbon Dioxide (CO_2)	g/kWh	0.0	0.0	241.1	500.7	690
Sulfur Oxides (SOx)	g/kWh	0.0	0.0	0.0	0.0	2.10
Methane (CH_4)	g/kWh	0.0	0.0	0.0	0.0	0.09
Hydroxide (OH)	g/kWh	0.254	0.031	0.000	0.138	-
Particulate Matter (PM)	g/kWh	0.00	0.00	0.00	0.00	0.73
Overall Efficiency	%	54.6	45.2	51.7	49.6	43

OVERALL CONCLUSIONS

- SOFC-Hybrid Systems in table above have higher overall efficiencies and produce substantially less CO_2, NOx, SOx, and PM when compared to the diesel engine shown

- Highest overall efficiency achieved in this study was slightly less than 55% based on the operation of the SOFC w/gas-turbine & single-pressure steam turbine (GT-1P) hybrid system

- In most cases, using a gas turbine improved overall efficiency because:
  - The heat of compression in air and fuel compressors reduced the load on the fuel and air heaters and resulted in a higher afterburner exhaust temperature.
  - The higher SOFC operating pressure resulted in higher cell voltage and more power per unit fuel.