SECA
Solid Oxide Fuel Cell Program

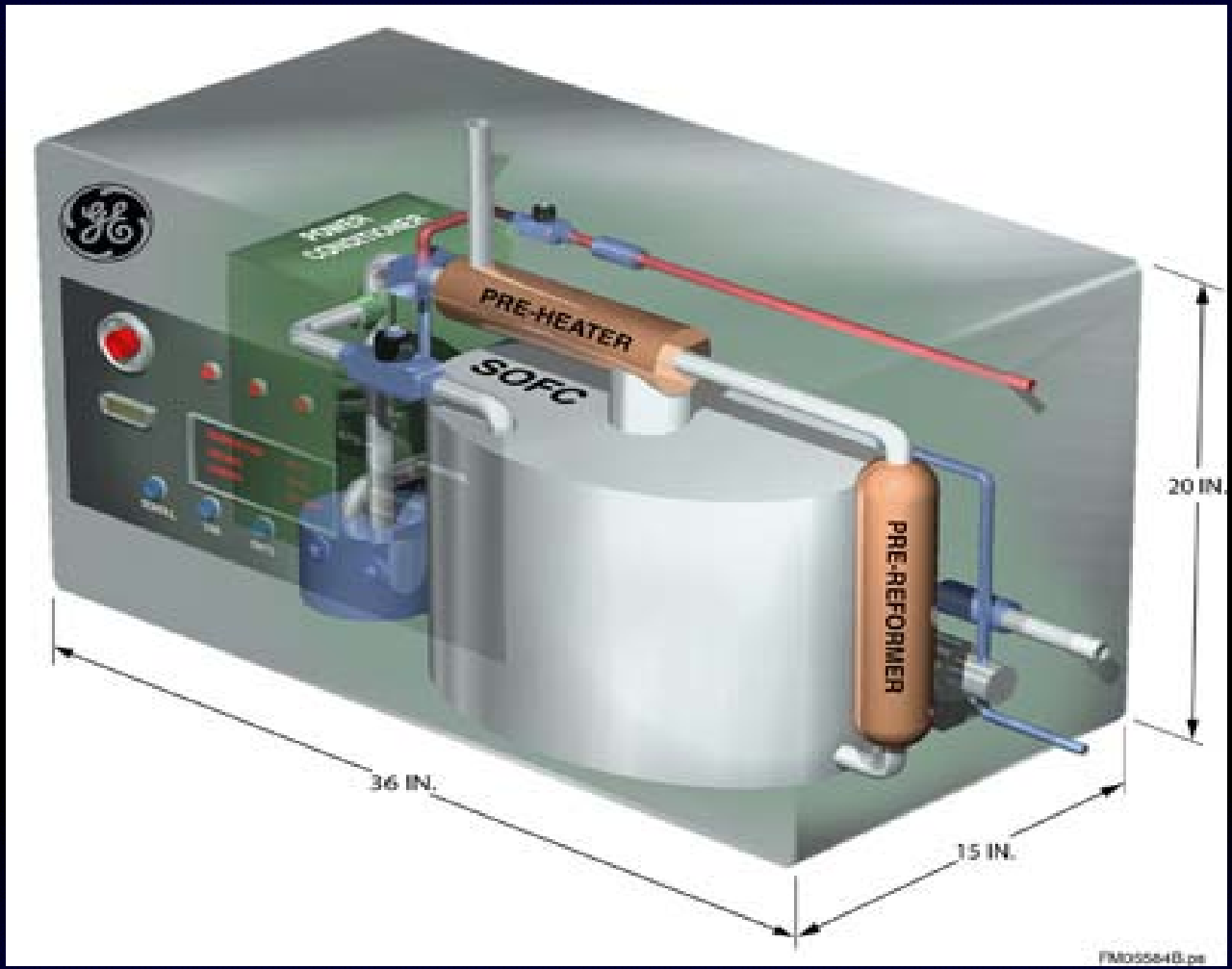
Fourth Annual Solid State Energy Conversion Alliance Meeting
April 15-16, 2003
Seattle, WA

Program Objective

- Overall objective
  - Demonstrate a fuel-flexible, modular 3-to-10-kW solid oxide fuel cell (SOFC) system that can be configured to create highly efficient, cost-competitive, and reliable power plants tailored to specific markets
- Development team
  - GE Power Systems
    - Torrance, CA
    - Schenectady, NY
    - Greenville, SC
  - GE Global Research
    - Niskayuna, NY

SOFC System Concept

GE Hybrid Power Generation Systems

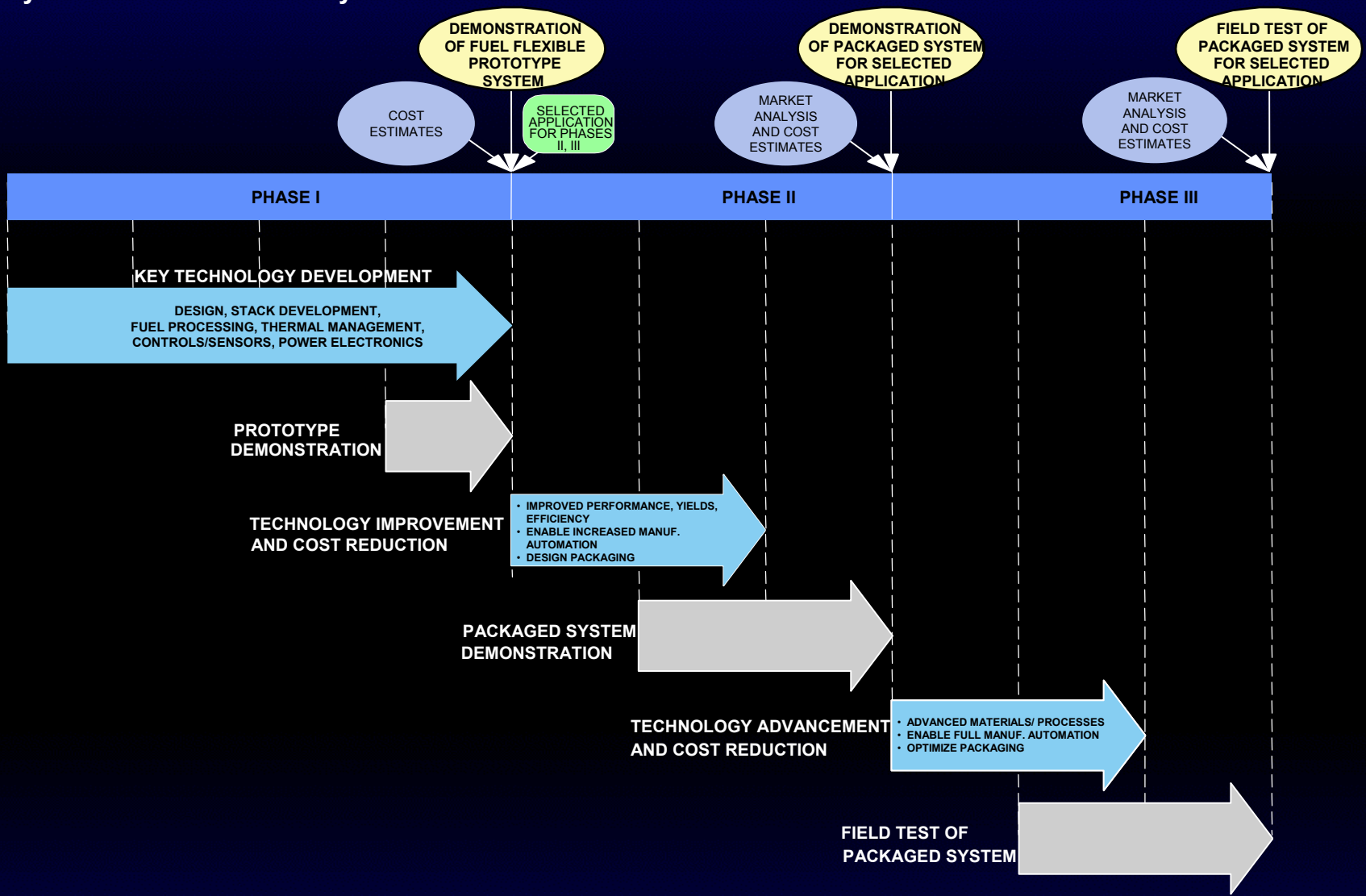


Key System Features

- SOFC
  - High-performance reduced-temperature cells
  - Operation on light hydrocarbons
  - Tape calendering manufacturing process
- Fuel processor
  - Low-cost, fuel-flexible fuel processor design
  - Catalytic process
  - Pre-reforming function
- Other subsystems
  - Integrated thermal management
  - Flexible control subsystem

Program Features

GE Hybrid Power Generation Systems



Phase I Work Elements

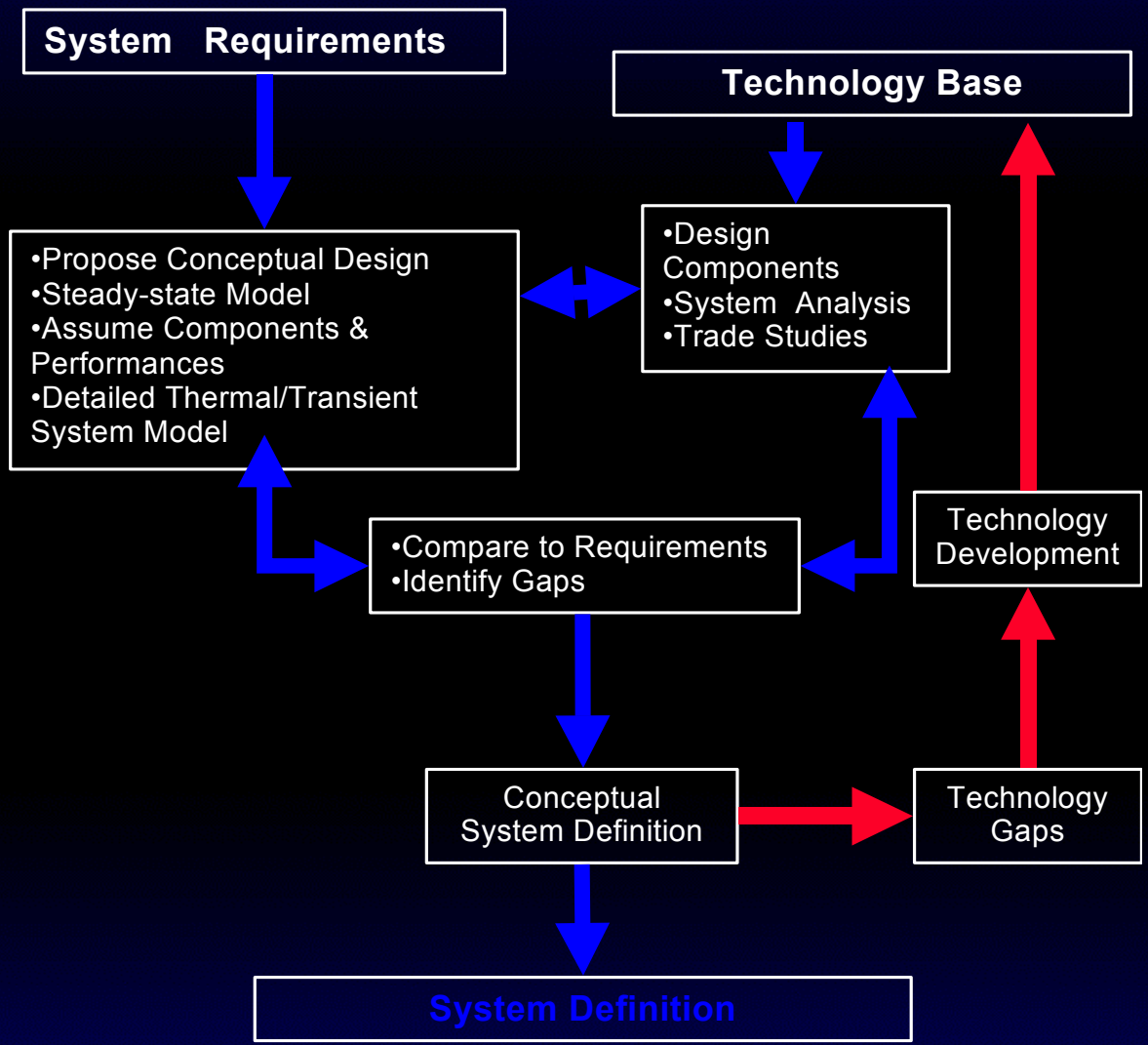
- System analysis
- Cost estimate
- Stack technology development
- Fuel processing
- Thermal management
- Control and sensor development
- Power electronics
- System prototype demonstration

Development Approaches

- System approach
  - Design for Six Sigma
- Development focus to meet SECA targets
  - High performance
  - Low cost
  - Reliability
  - Modularity
  - Fuel flexibility

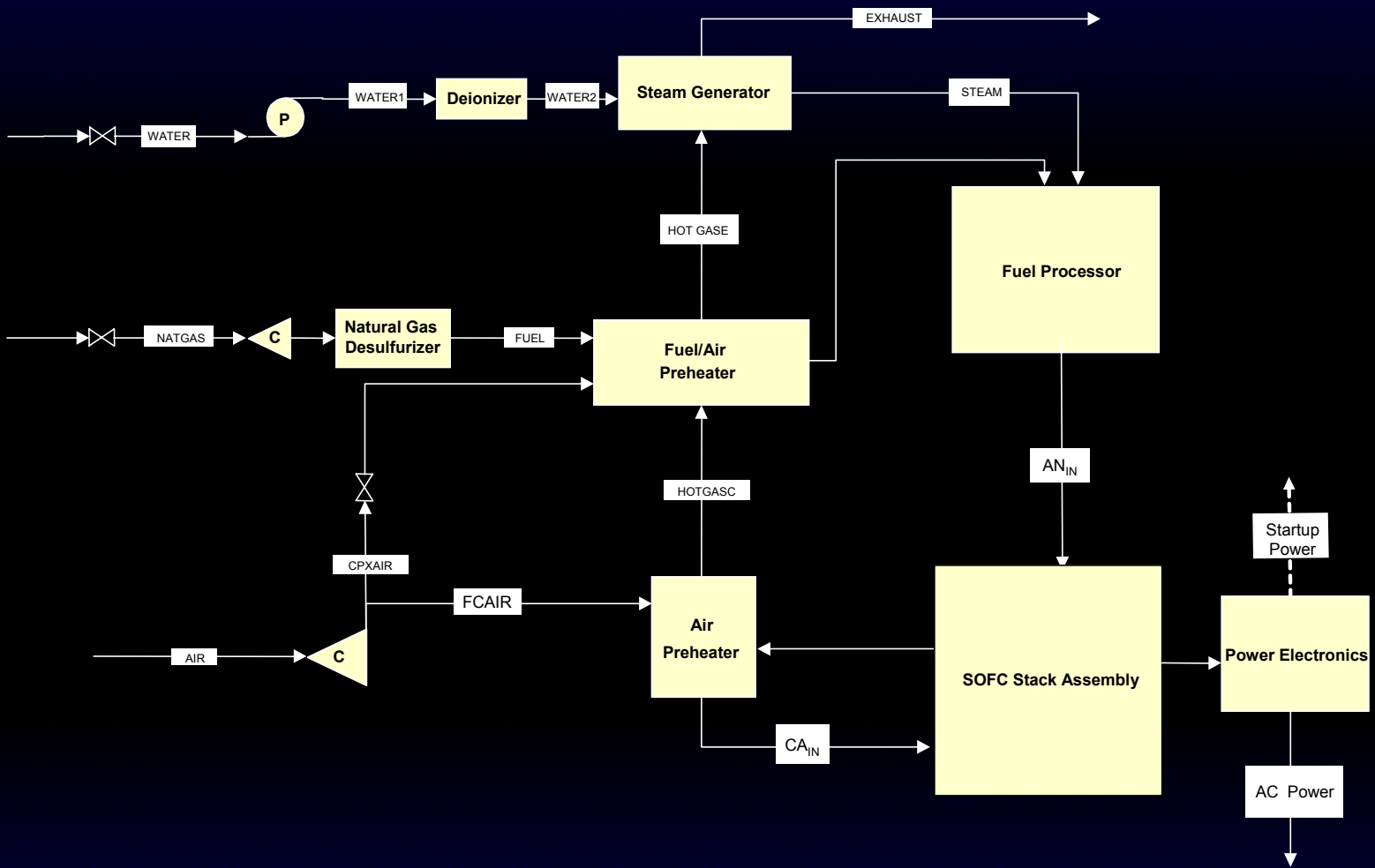
System Design and Analysis Approach

GE Hybrid Power Generation Systems



Baseline System Concept

GE Hybrid Power Generation Systems



Performance Estimates

GE Hybrid Power Generation Systems

	Stationary (Baseline)	Mobile	Military
Fuel	Natural Gas	Gasoline	Diesel
Input			
Fuel, lb/hr	2.0	2.0	1.7
Air, lb/hr	186	185	188
Water, lb/hr	2.3	4.9	4.2
Power			
Fuel cell, kW	5.8	4.4	3.2
Net, kW	5.0	3.7	2.5
Efficiency			
Net, %	40	33	28

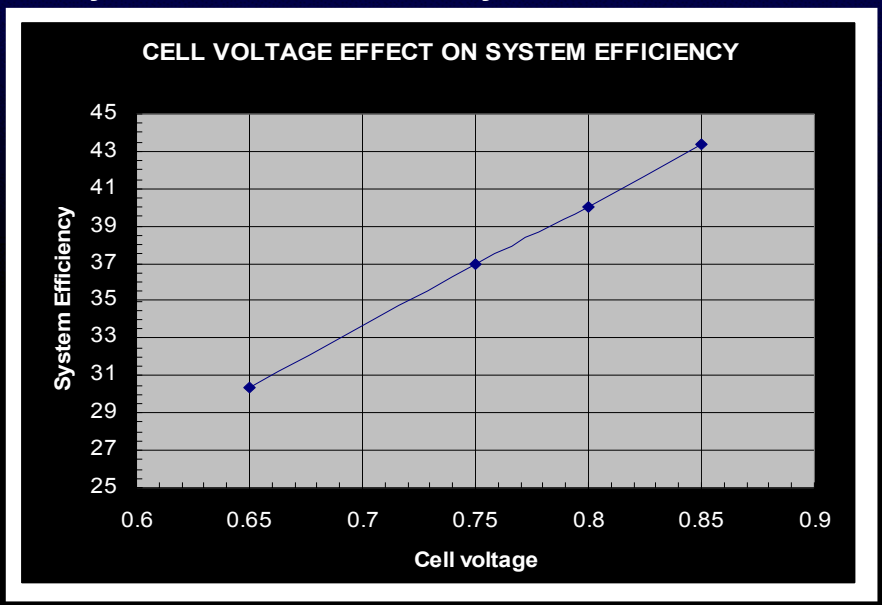
Important Performance Parameters

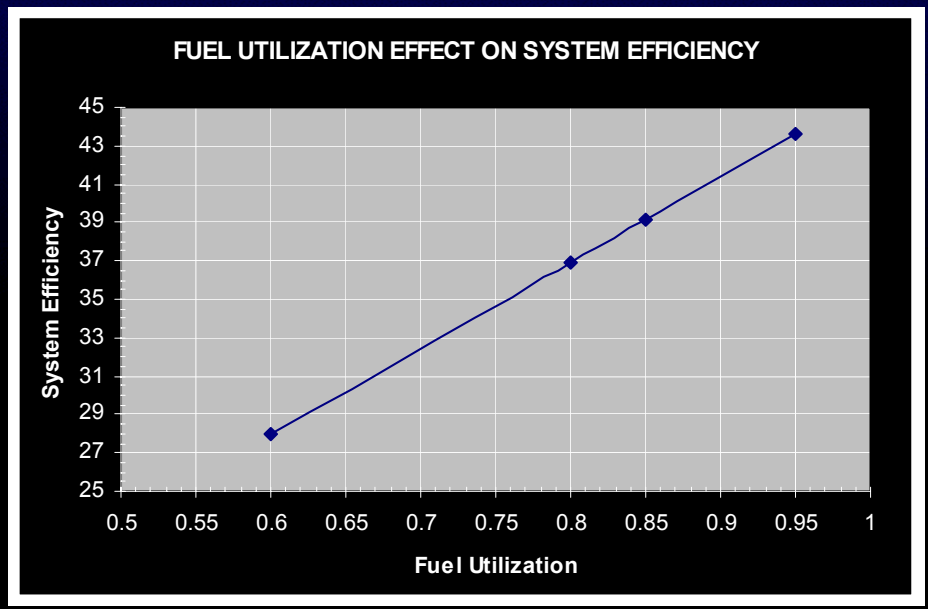
GE Hybrid Power Generation Systems

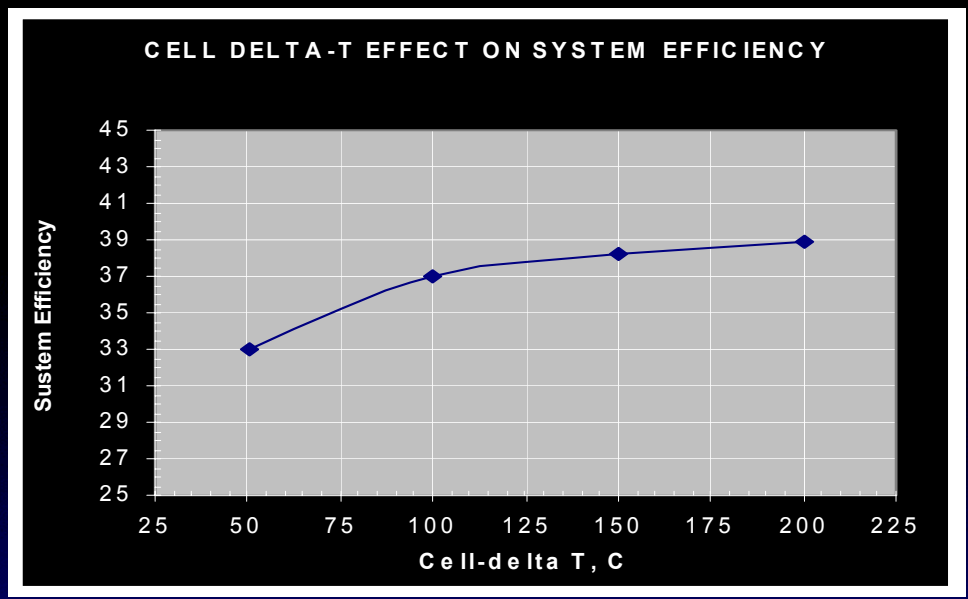
SOFC STACK	Average cell voltage
	Stack voltage
	Fuel utilization
	Cell temperature rise
	Cell pressure drop
	Anode leakage fraction
	Internal Reforming fraction
	Heat loss
FUEL PROCESSOR	Steam to carbon ratio
	Carbon to oxygen ratio
	Operating temperature
	Feed Temperature
	Approach to Equilibrium
	Pressure drop
	Heat loss
HEAT EXCHANGERS & THERMAL MANAGEMENT	Pressure drops
	Heat losses
AIR DELIVERY	Compressor Efficiency
	Compressor pressure ratio
POWER ELECTRONICS & ELECTRICAL COMPONENTS	Inverter efficiency
	Motor efficiencies

Stack Parameter Effects on System Performance

GE Hybrid Power Generation Systems

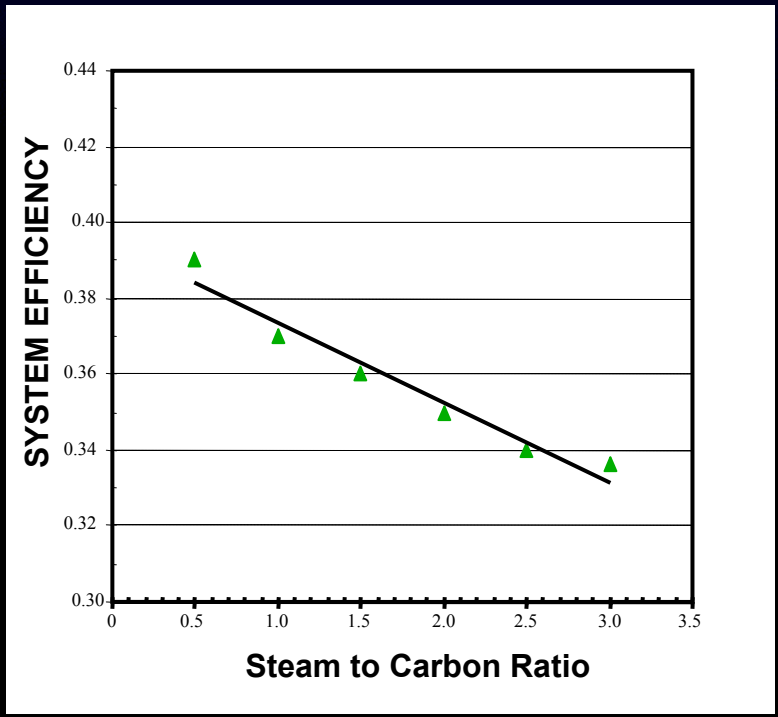


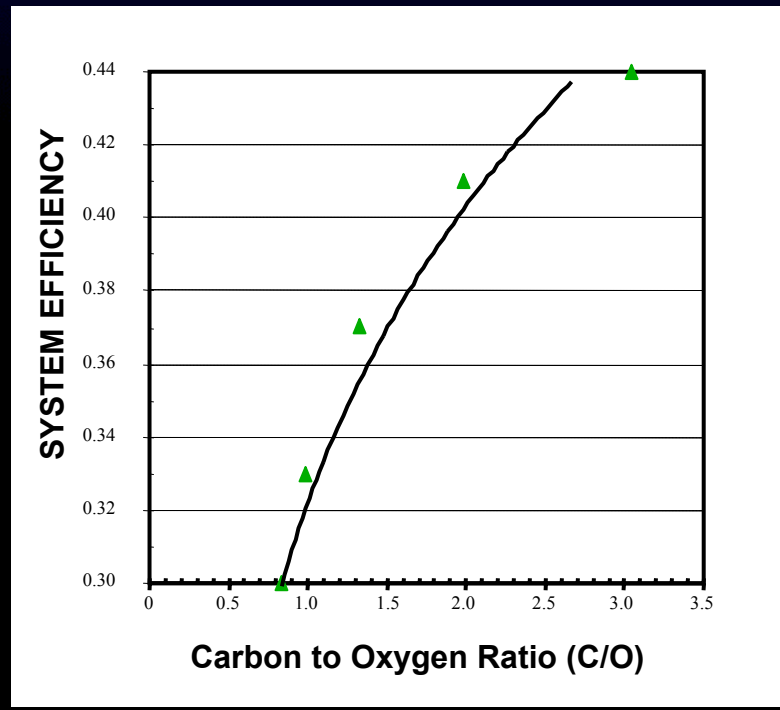




Fuel Processor Effects on System Performance

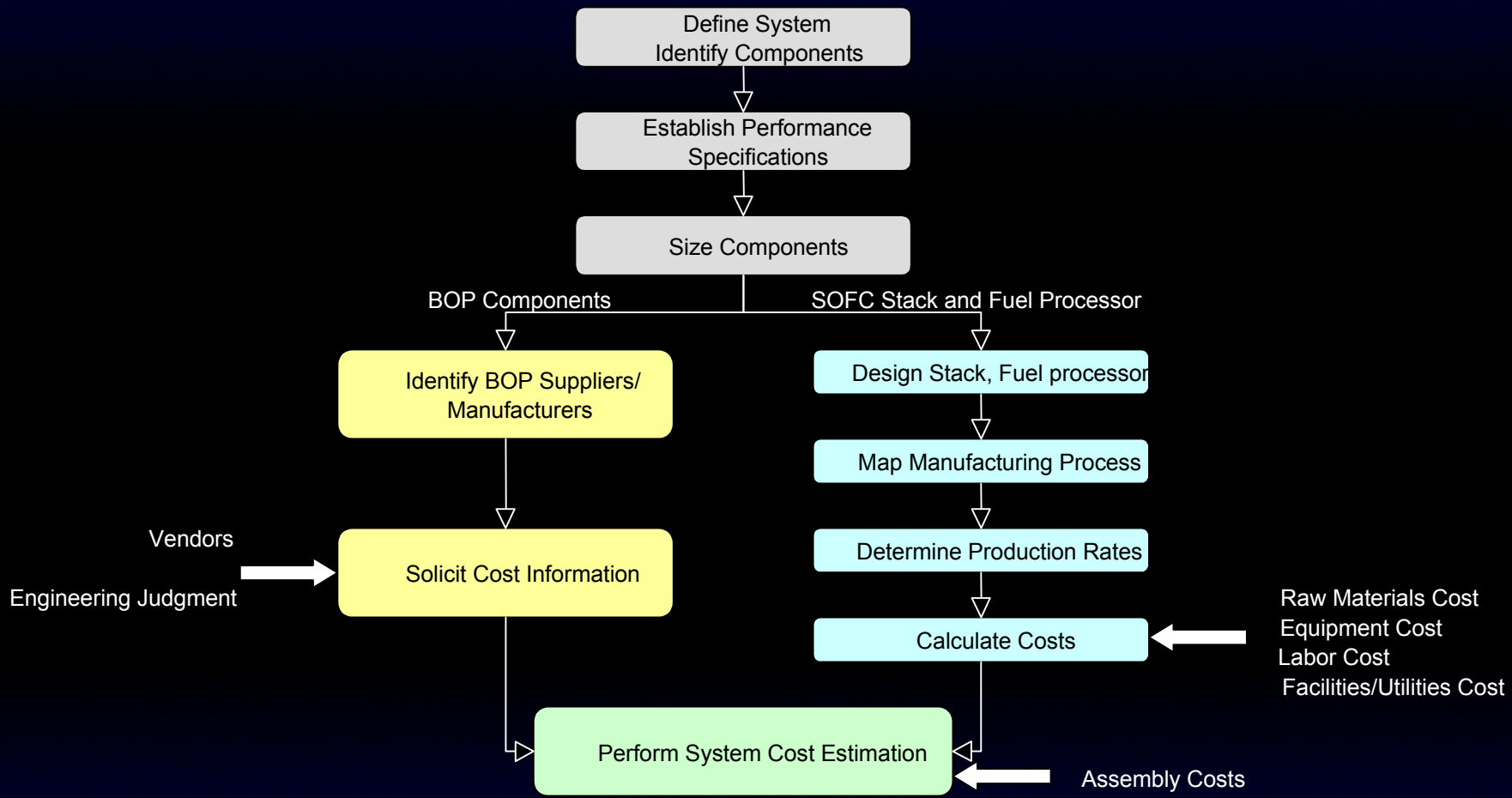
GE Hybrid Power Generation Systems





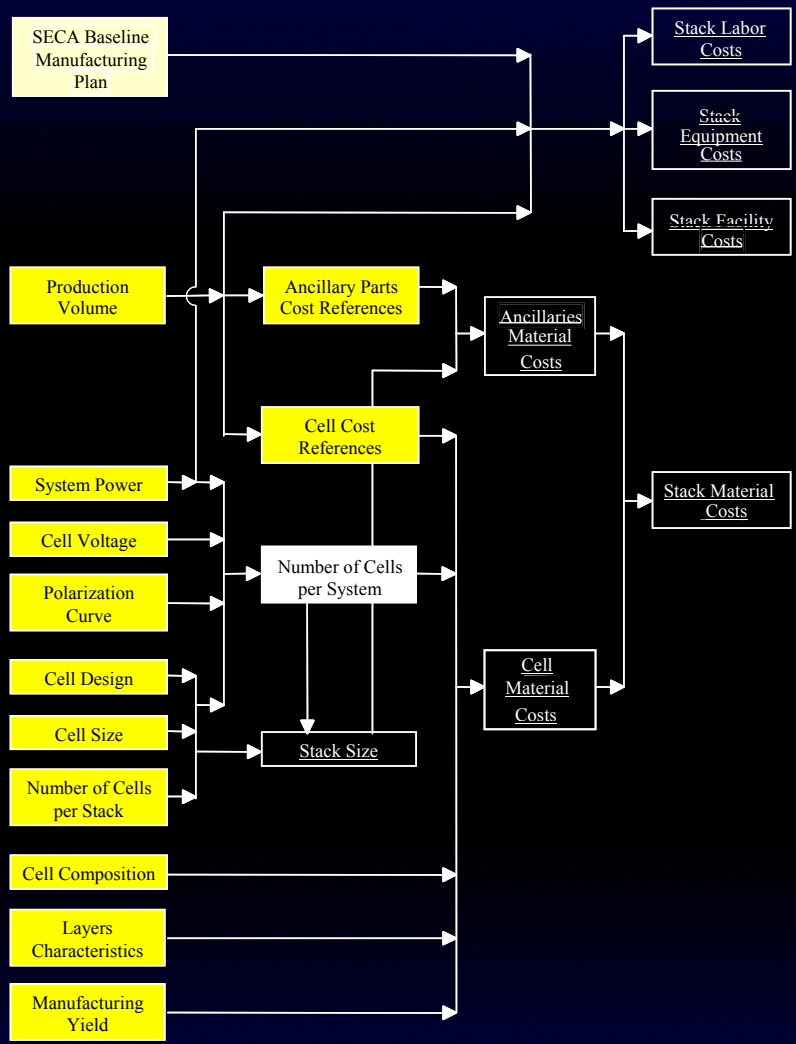
Schematic of Method for Cost Estimation

GE Hybrid Power Generation Systems



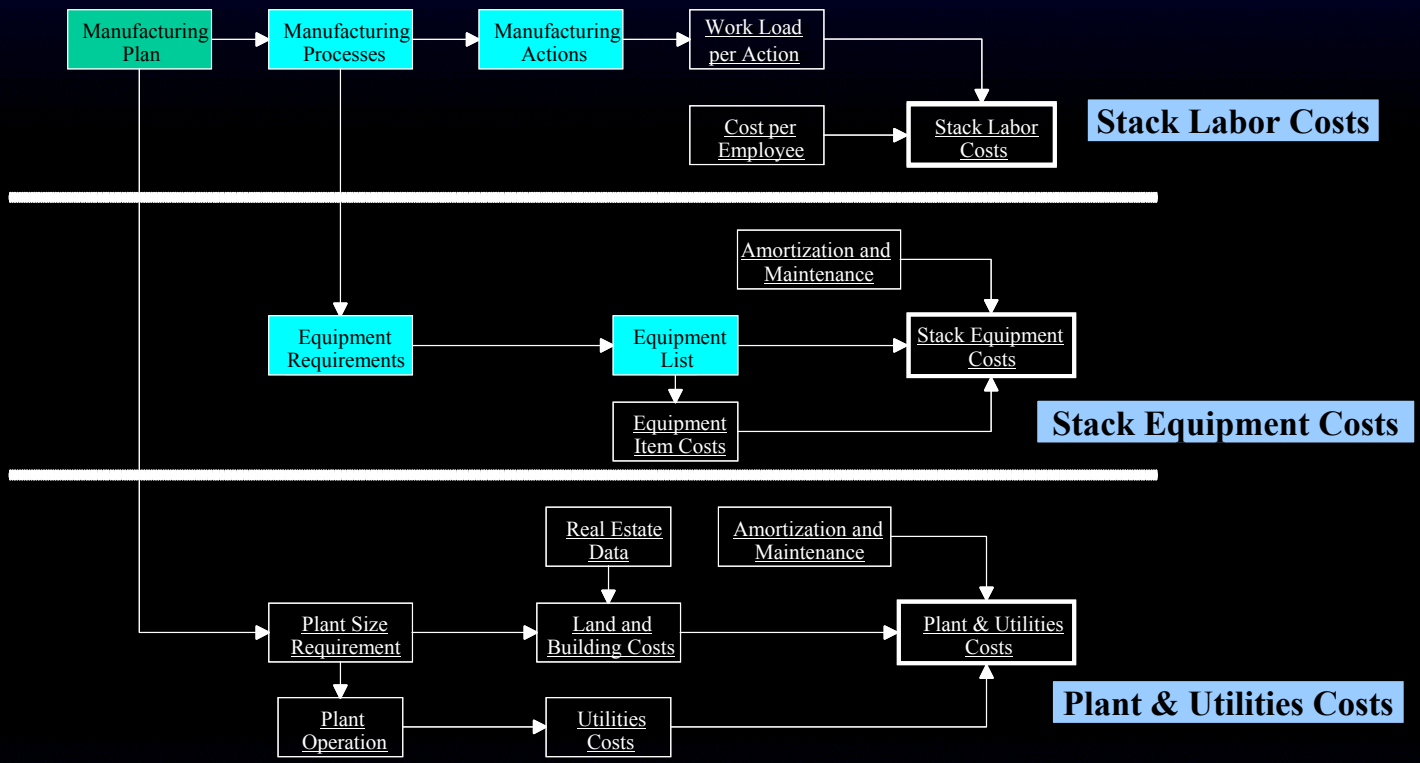
Stack Material Cost Estimates

GE Hybrid Power Generation Systems



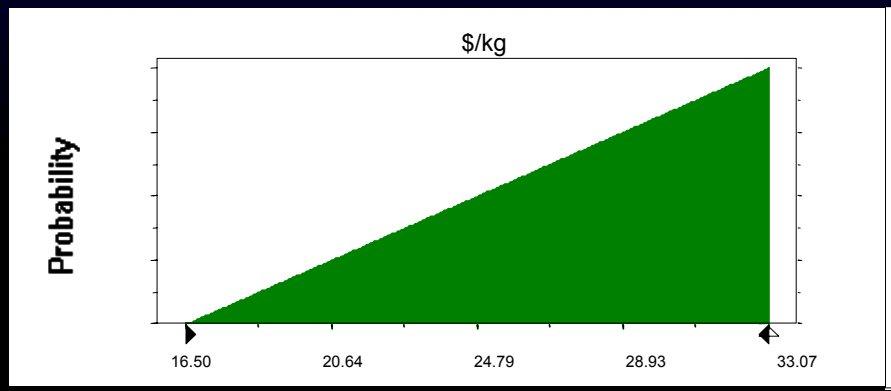
Stack Manufacturing Cost Estimates

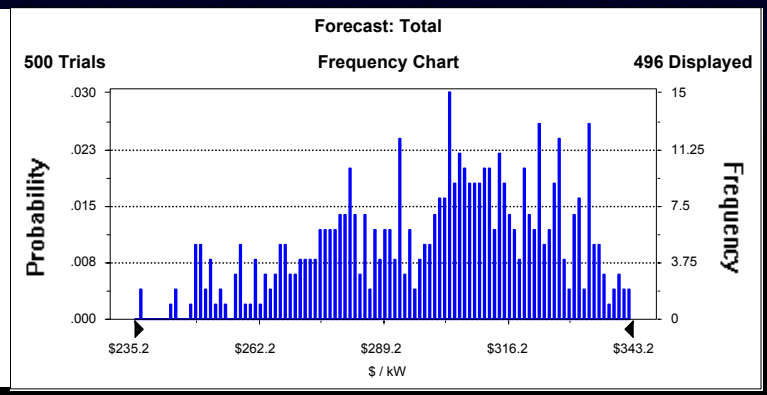
GE Hybrid Power Generation Systems

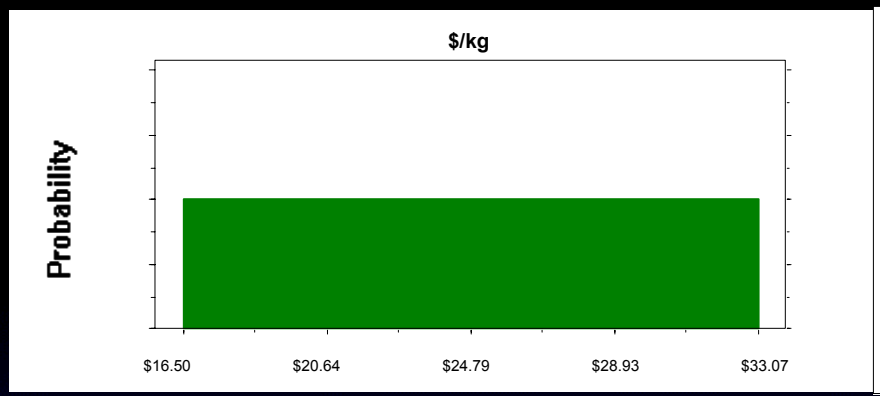


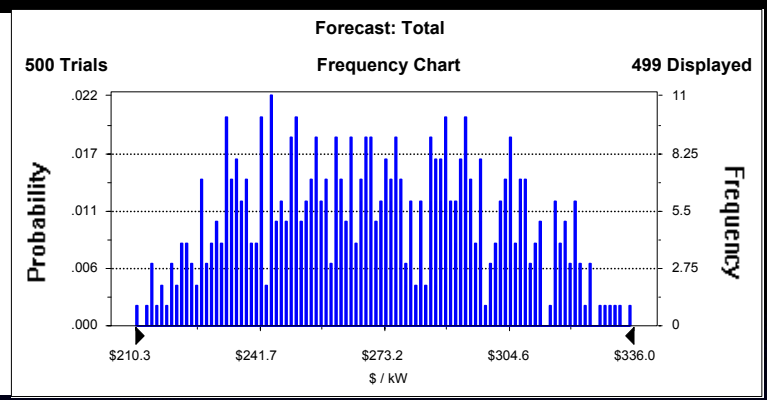
Stack Cost : Monte Carlo Simulation Examples

GE Hybrid Power Generation Systems

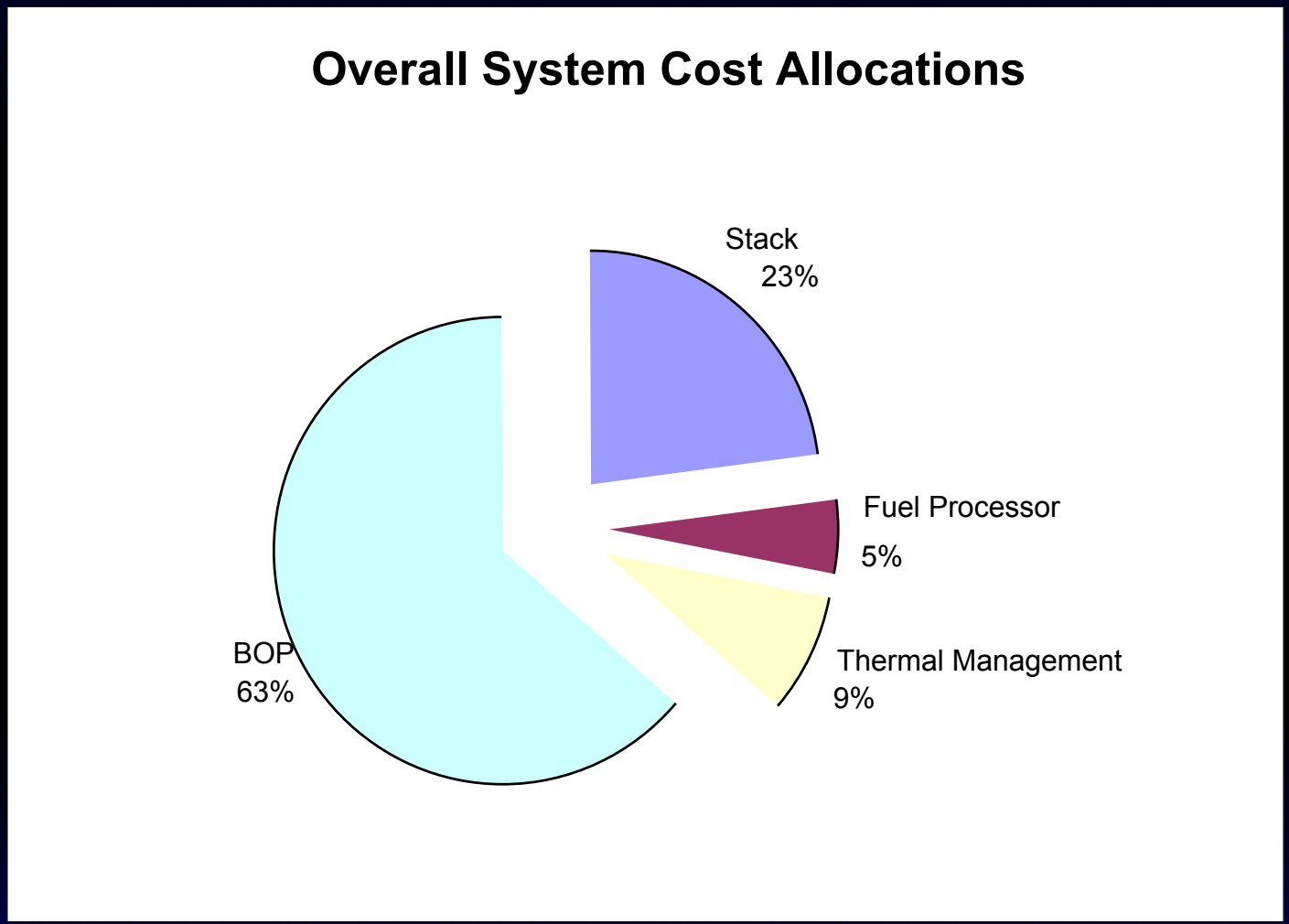






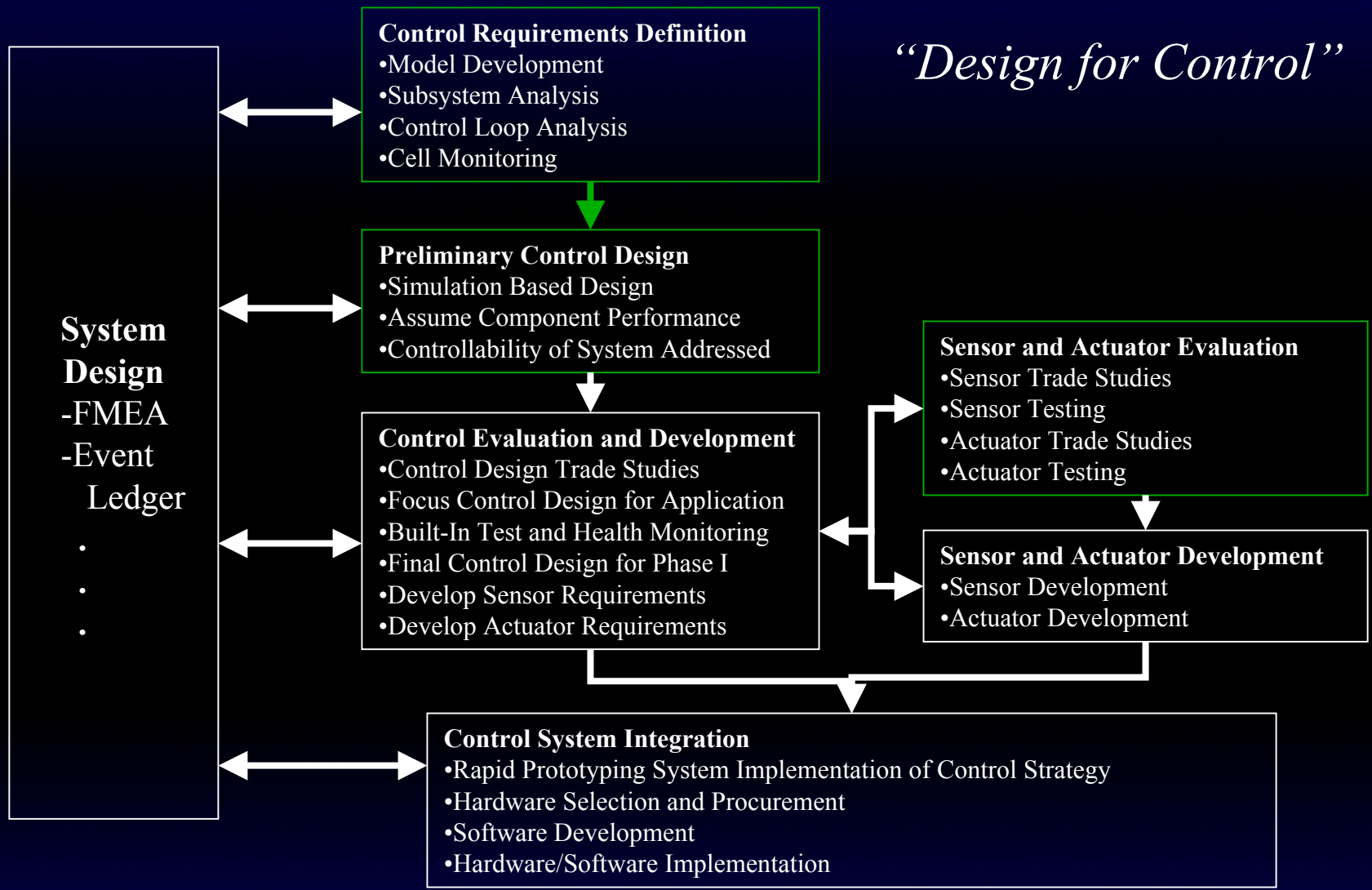


GE Hybrid Power Generation Systems



Controls Analysis and Design Process

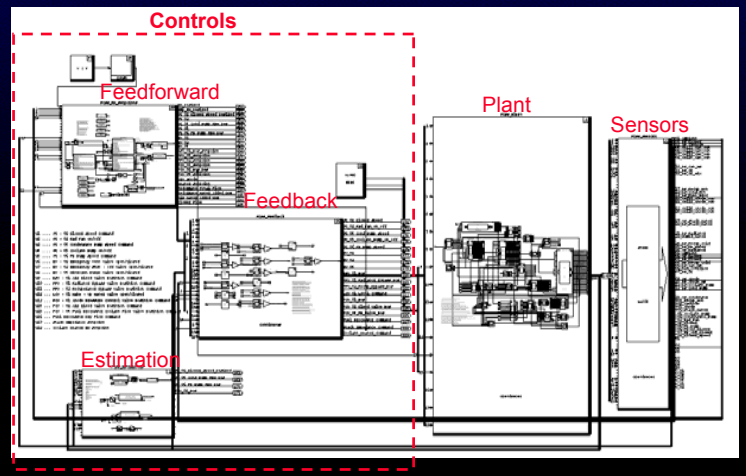
GE Hybrid Power Generation Systems



"Design for Control"

Control & Sensing Approach

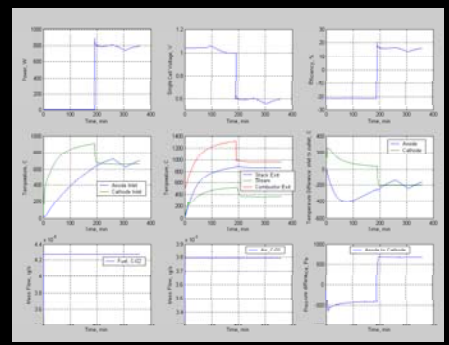
- GE Fuel Cell Dynamic Component Library
  - Dynamic Component Models
  - Dynamic Subsystem Models
  - Dynamic System Models
  - Control System Design
  - Simulation Trade Studies
- Rapid Prototyping of Control Systems
  - Rapid Test Development
  - Hardware-in-the-Loop Simulations and Tests
  - Automatic Code Generation
- Hardware Implementation and Validation of most Promising Control System Design



Rapid Prototyping

This approach allows for low-cost investigation of advanced control techniques which provide significant system cost and performance breakthroughs

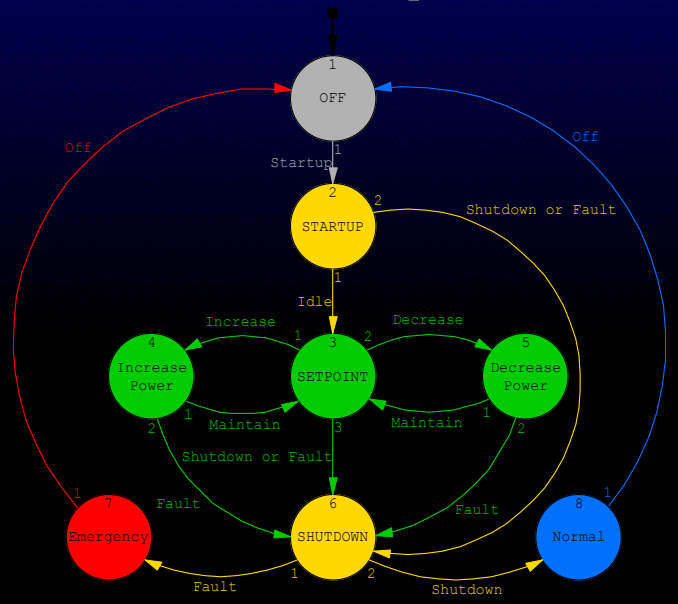
- Four start-up strategies have been identified
- Simulation based trade studies are currently being conducted to optimize start-up strategy
- Control Requirements
  - Performance
  - Cost
  - Reliability
  - Safety

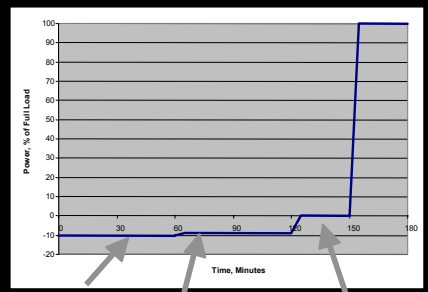


Brainstorm Strategies → Approach → Modeling → Optimized Start-up Strategy

Transient Operation

- **Transients seen during start-up and shut-down**
  - Temperature ramp rates on all components will be maintained
  - Component limitations accounted for explicitly in control system
- **Transients seen during normal operation**
  - Components maintained isothermally
  - Efficiency traded for system stability

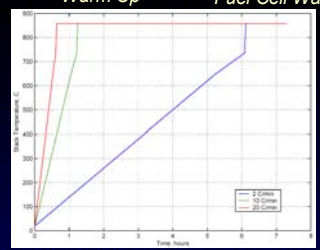




Fuel Processor & BOP Warm Up

Fuel Cell Warm Up

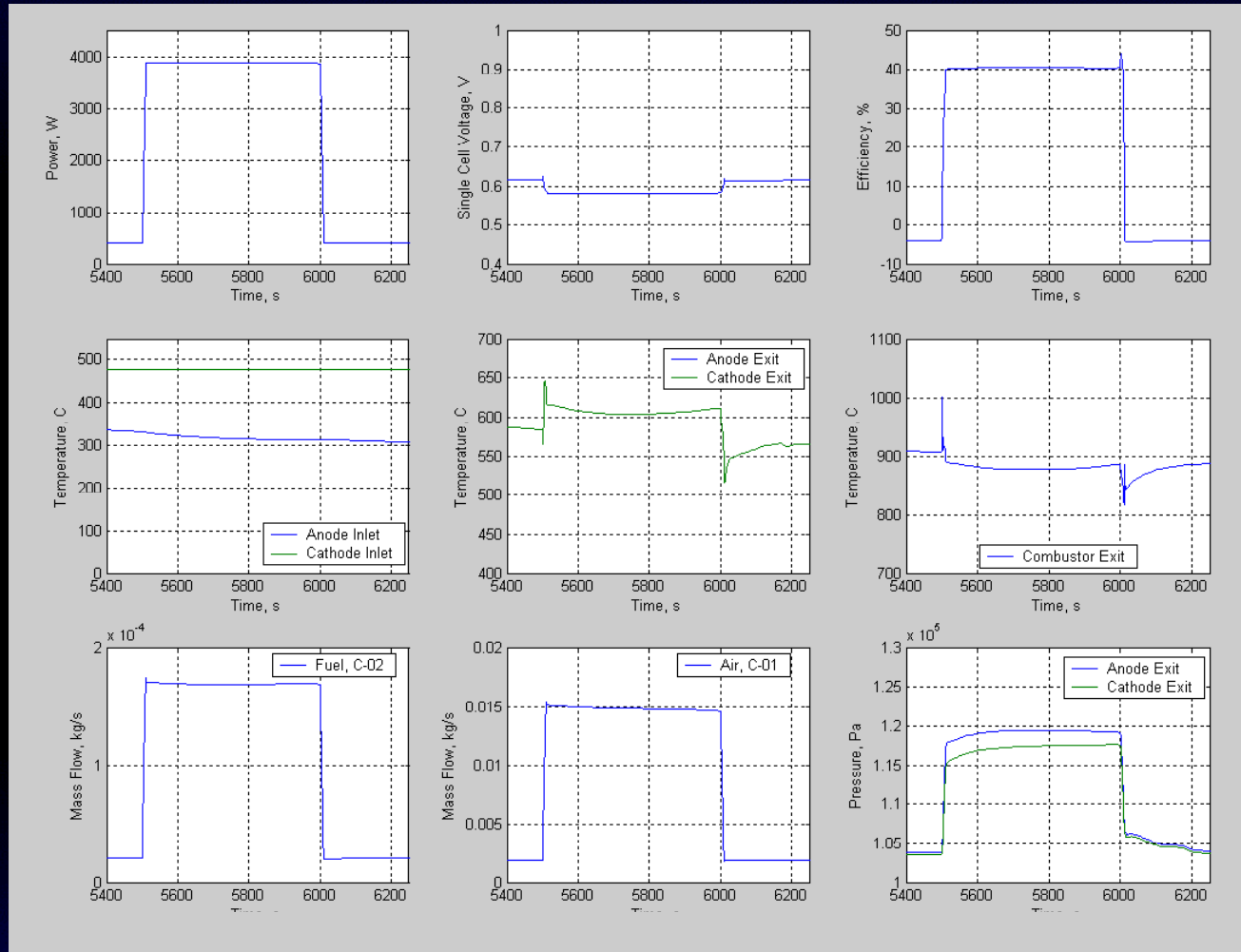
Test Load and Standby



SECA Dynamic System Model - Ramp Results

GE Hybrid Power Generation Systems

- Ramp increase in power from 0% to 75% load in 10 seconds
- SOFC temperature too low resulting in poor performance
  - Anode inlet temperature low
  - Cathode inlet temperature low
- Direct ramping of system seems promising, but further analysis is needed

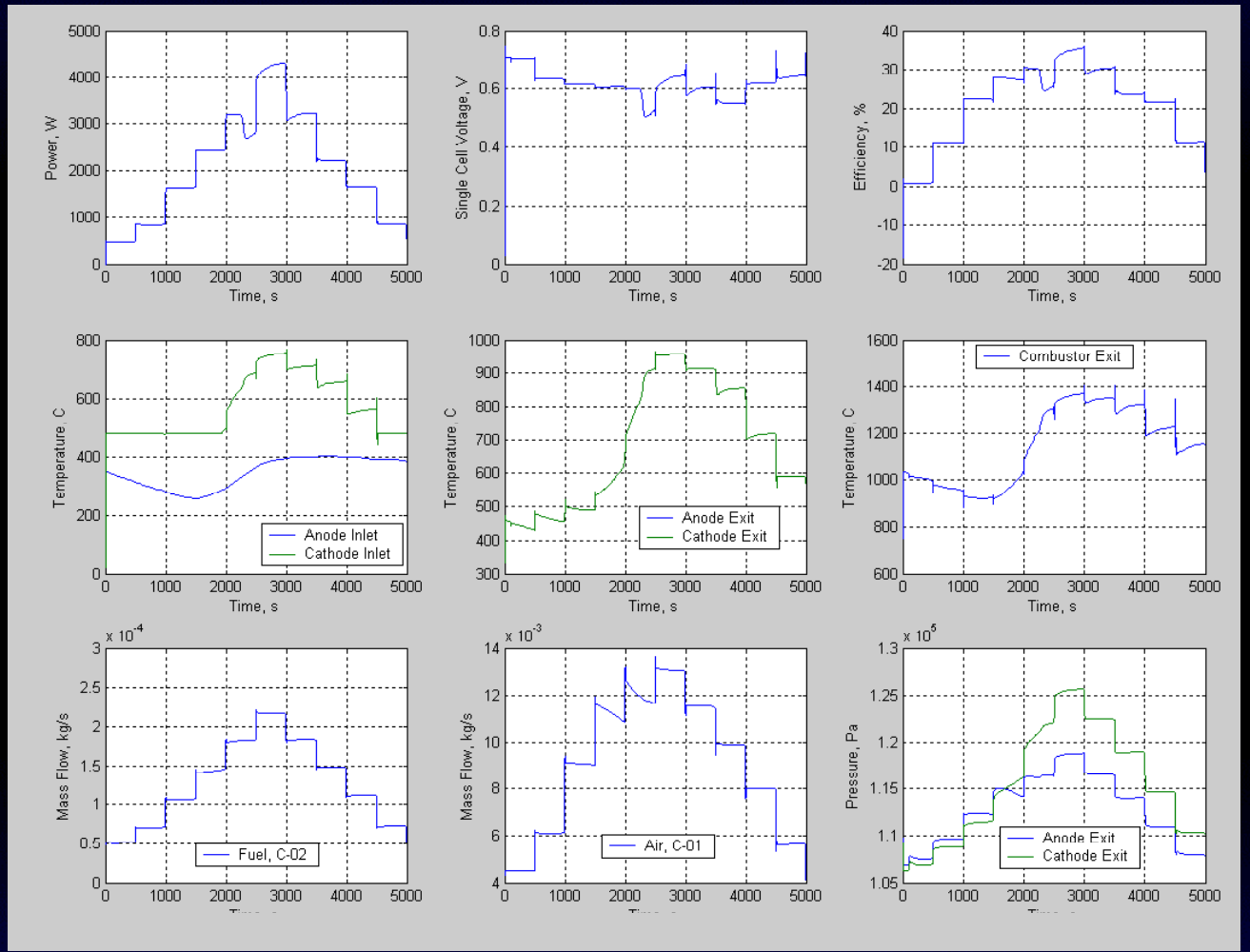


Preliminary Results

SECA Dynamic System Model - Step Results

GE Hybrid Power Generation Systems

- ~0.5 kW steps
- SOFC temperature control very sensitive
  - Steam-to-carbon
  - Air utilization
- Fuel cell performance low
  - High current density
  - High fuel utilization
- Stepping of power shows some stability benefits



Preliminary Results

Tape Calendering Process

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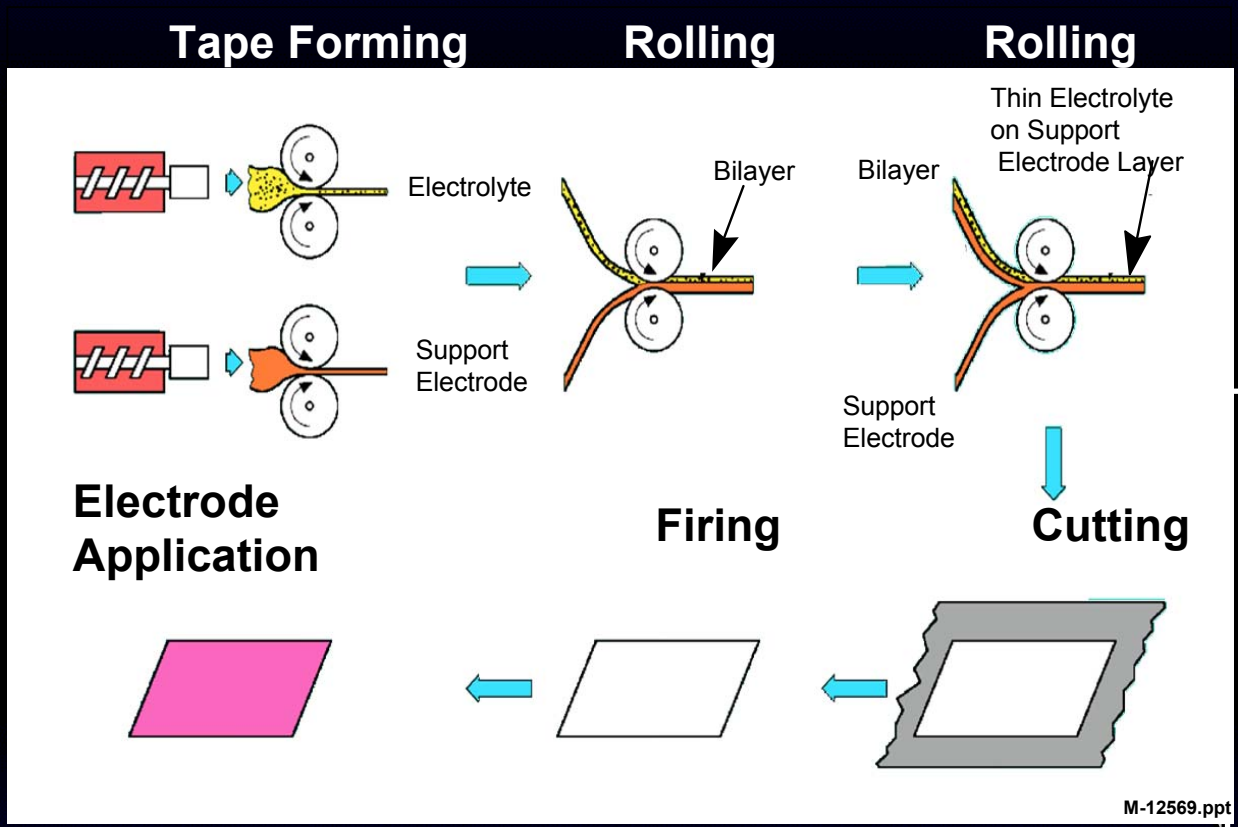
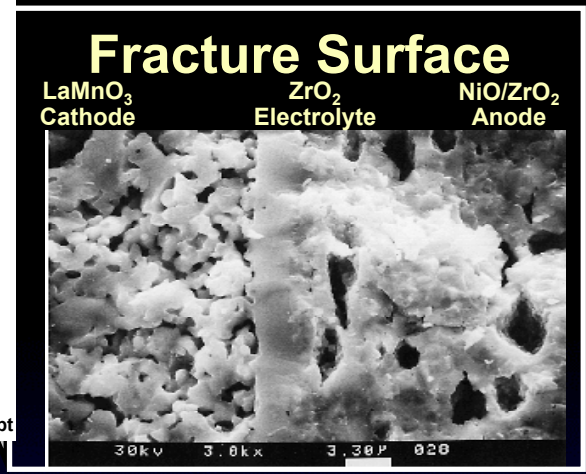
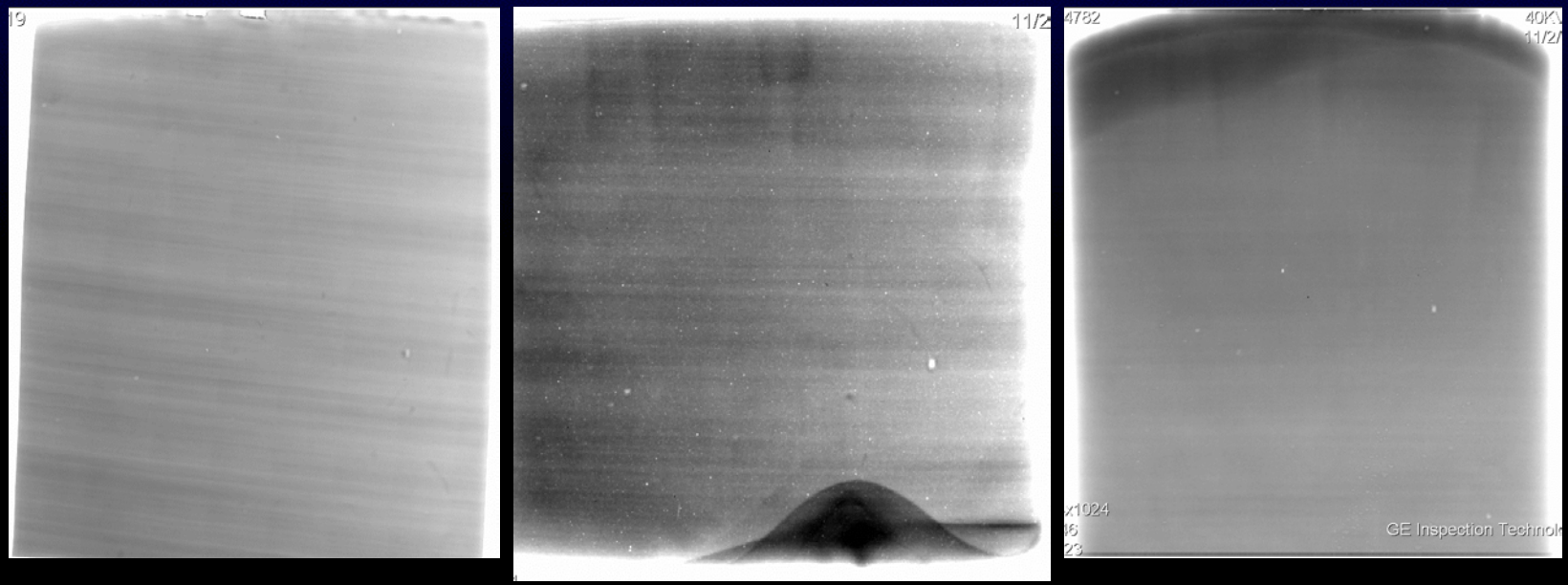




NDE Inspection of Green Tapes

GE Hybrid Power Generation Systems

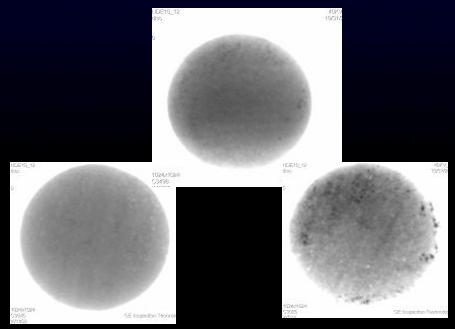


- X-Ray inspection of three tapes in various stages of processing, the radiographs show indications of higher and lower density regions

NDE Inspection of Sintered Bilayers

GE Hybrid Power Generation Systems

Optical Image



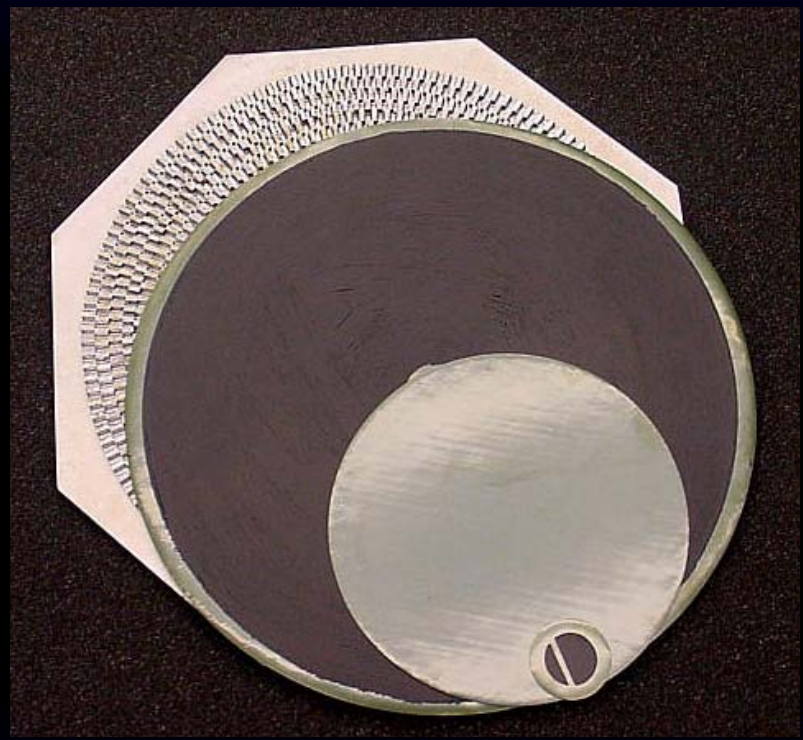
X-Ray Image

Ultrasonic Image

- Both X-Ray and ultrasonic imaging are being evaluated for fired bilayers
- Density variations can be observed with both techniques
- Ultrasonic more sensitive of surface features

Footprint Scale-Up

- Effects and issues related to foot-print scale-up are being explored
- 8” diameter cells and interconnects have been fabricated and tested



8”–Cell Stack Performance

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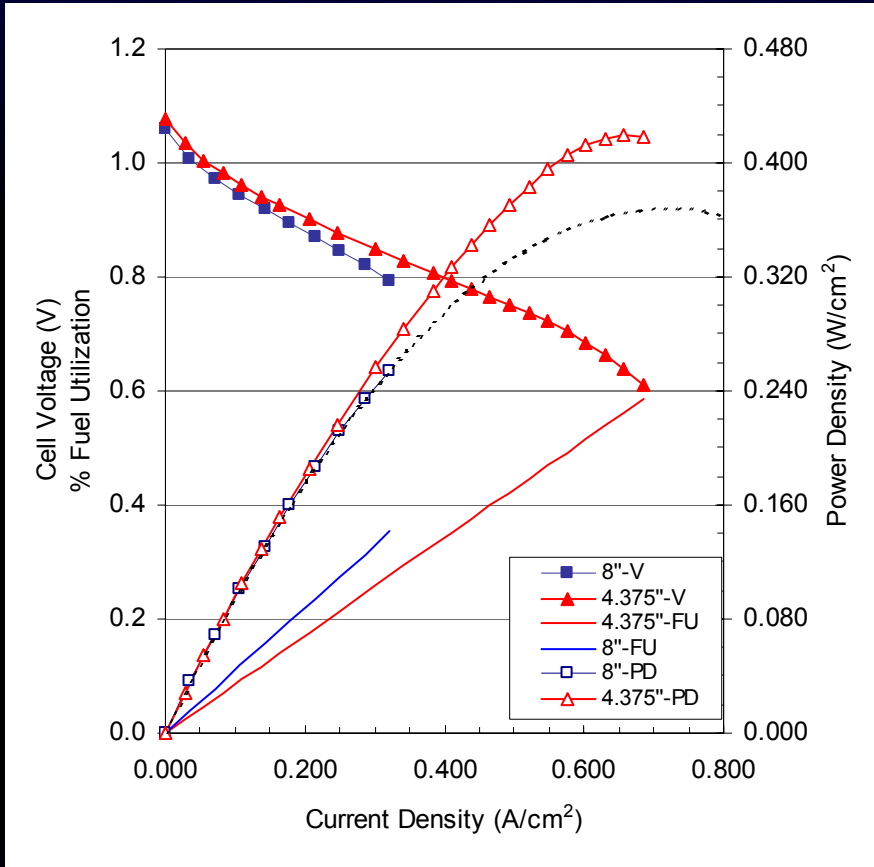
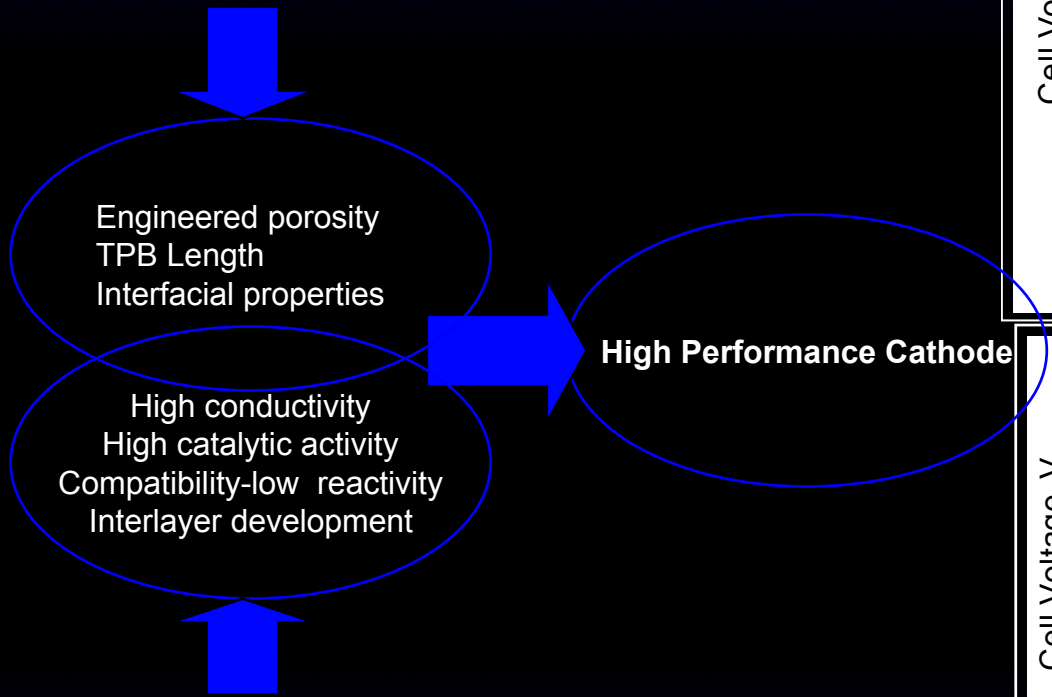


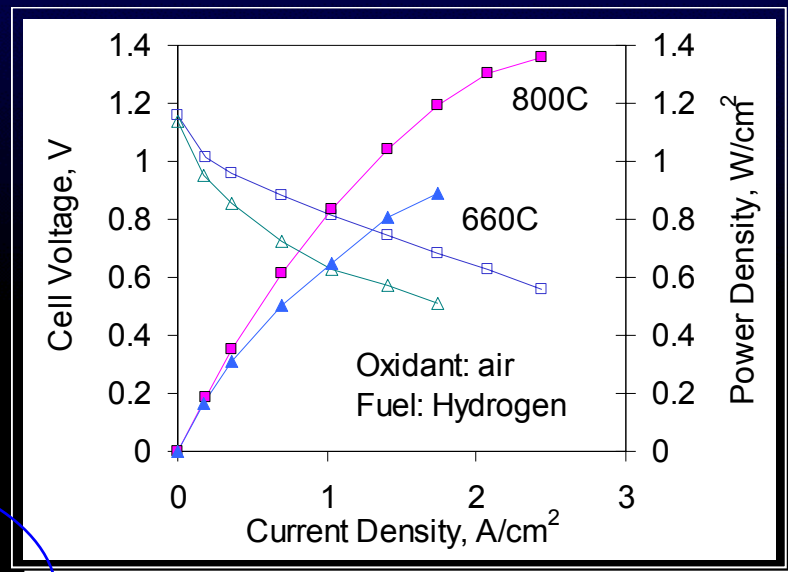
Cathode Materials and Microstructure Development

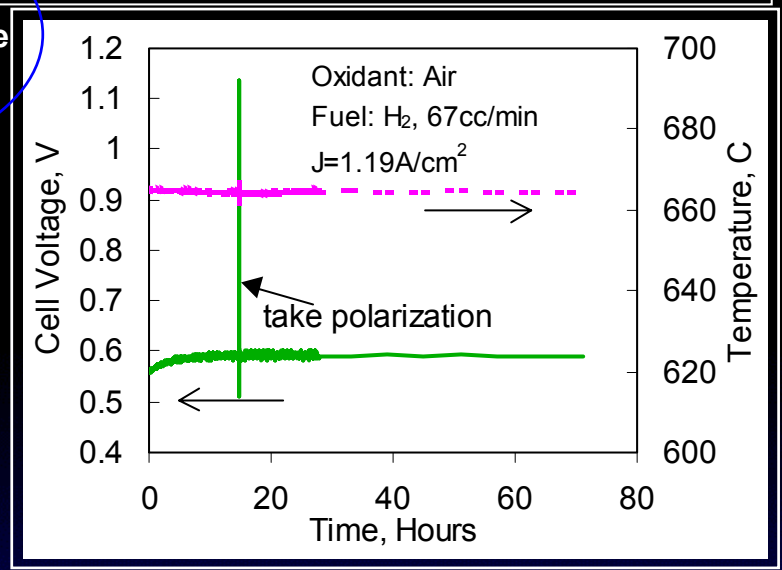
GE Hybrid Power Generation Systems

Engineered Structures



New Materials





Fuel Concentration and Utilization

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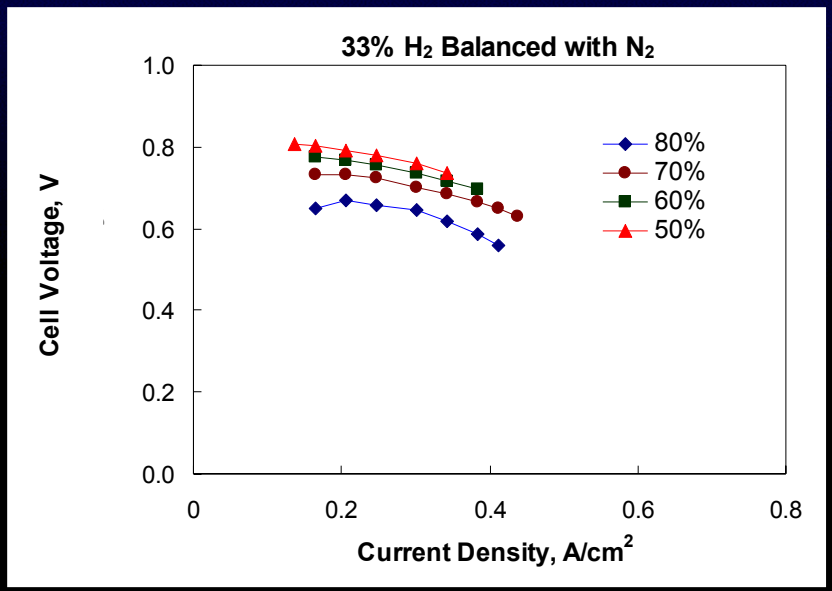
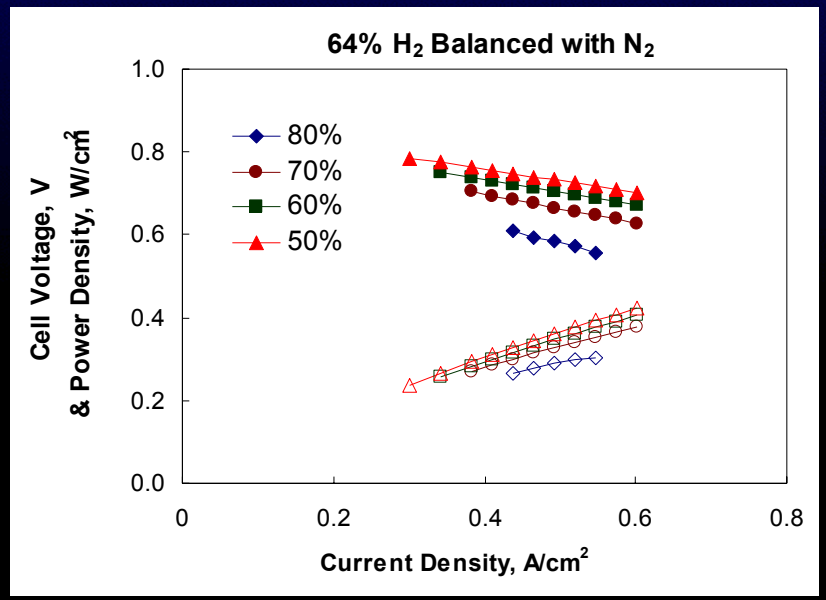
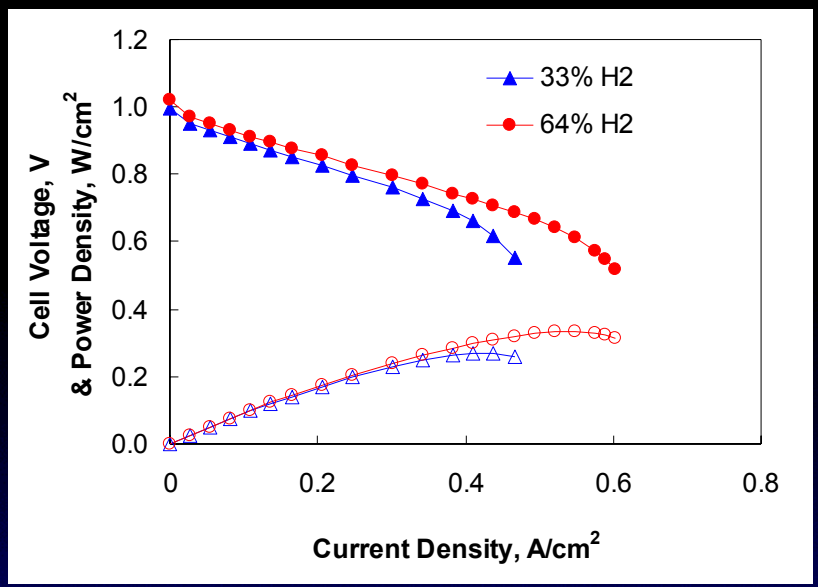






Mass transfer is a major issue for anode-supported SOFCs

$$i_l = \frac{-nFD_T P_{H2}}{\delta}$$

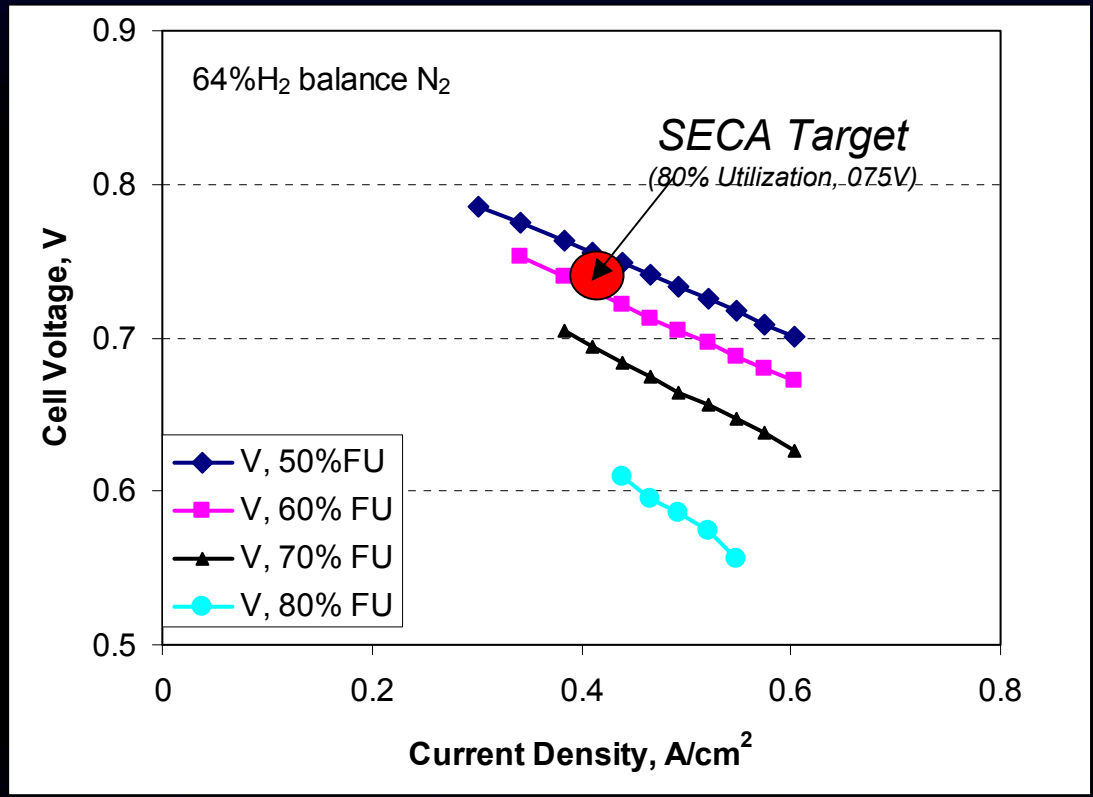
Anode Microstructure Development

GE Hybrid Power Generation Systems

Enhanced catalytic activities
Internal reforming capability
Sulfur tolerance

Engineered Porosity
Reduced thickness

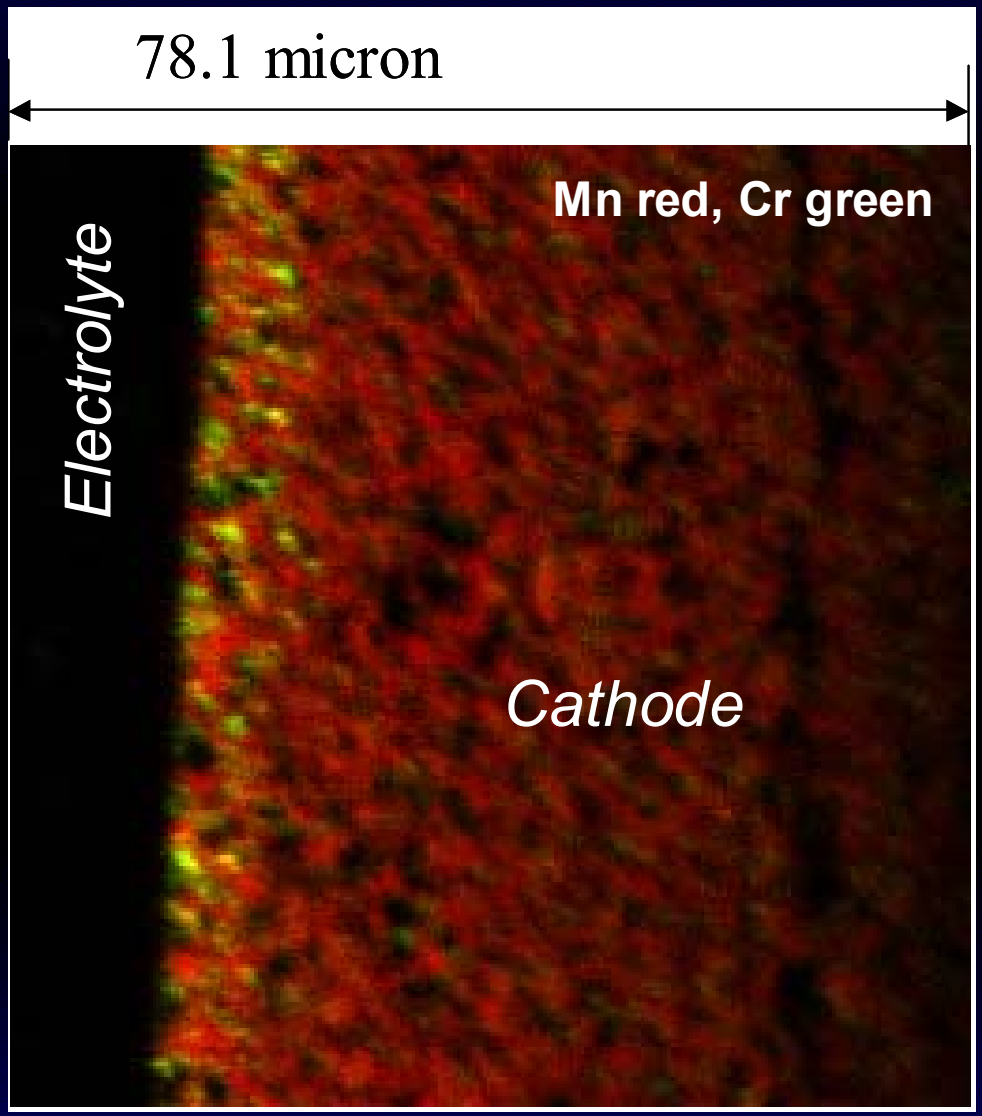
Low cost materials
Toughed support structures



Long-Term Testing

- Stacks tested up to 3000 hours
- Performance degradation (much higher than target) observed
- Potential causes for performance losses being investigated

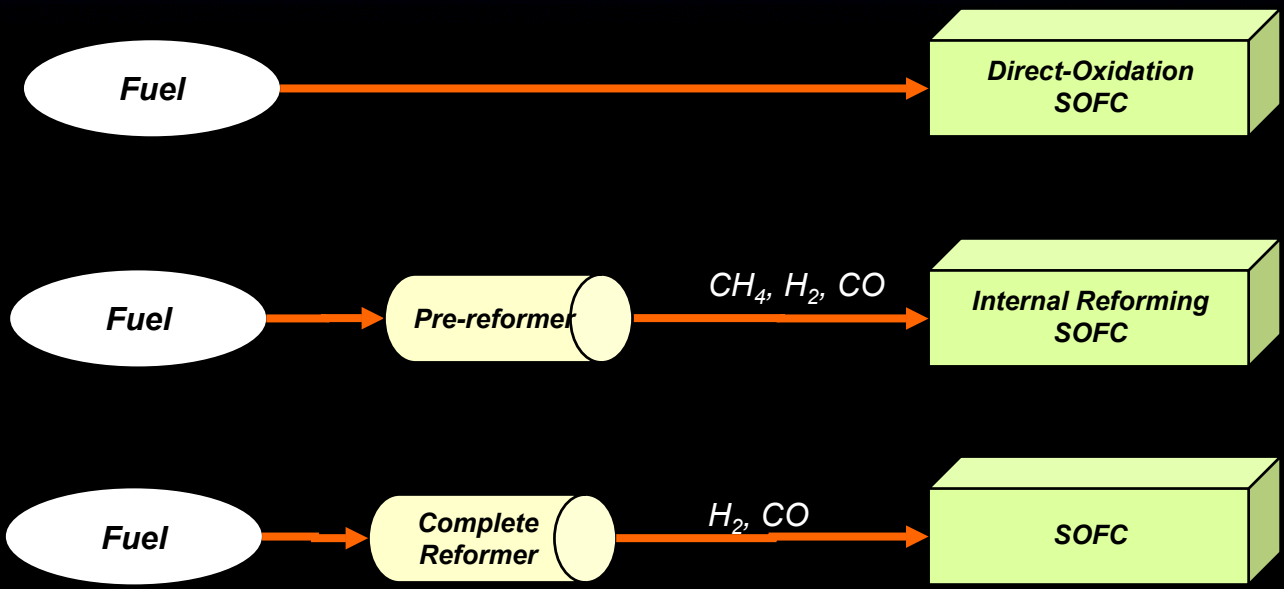
SIMS Results on 3000-hours Stack



- Chromium builds up at cathode-electrolyte interface
- Chromium is associated with manganese, not with lanthanum
- TEM underway to look at phases that are present

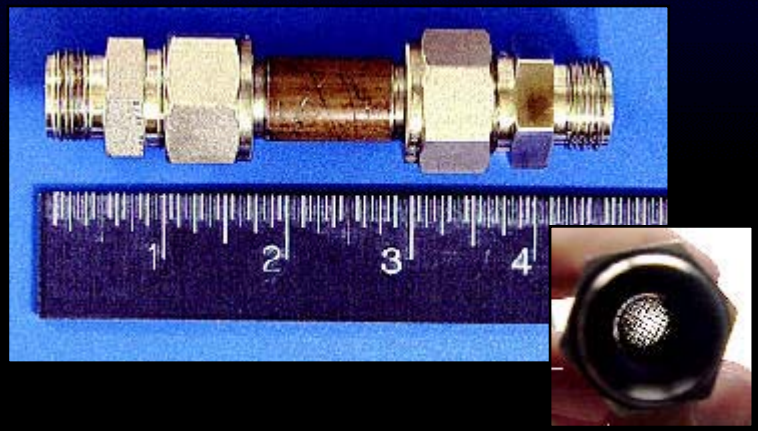
SOFC Operation on Hydrocarbon Fuels

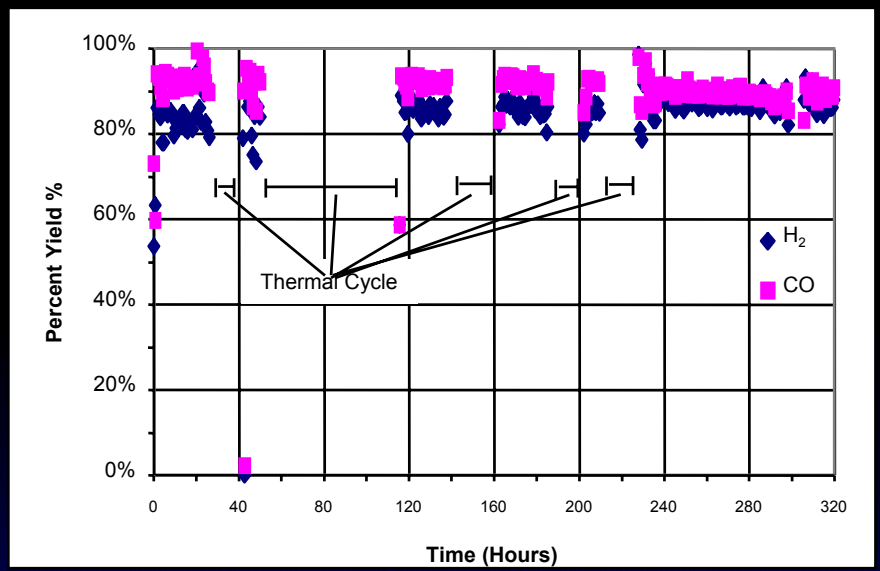
GE Hybrid Power Generation Systems



CPOX for Processing Hydrocarbon Fuels

GE Hybrid Power Generation Systems





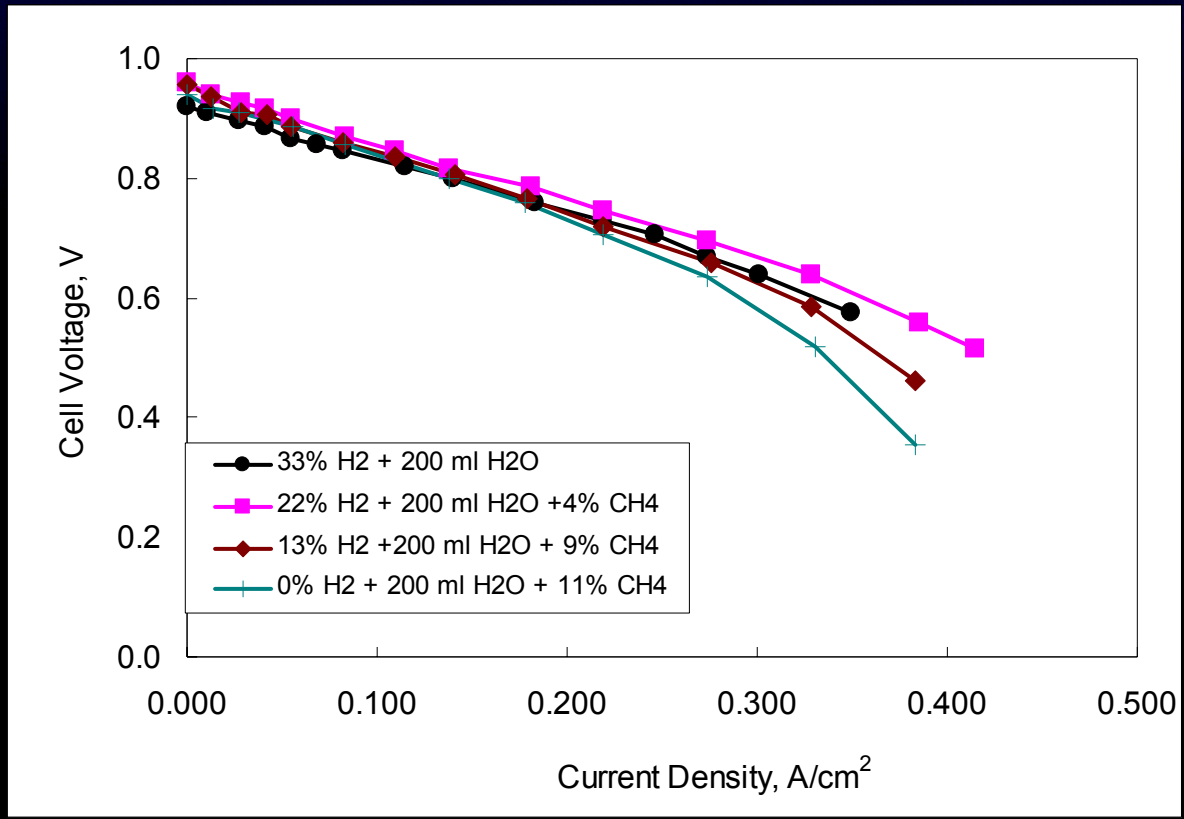
- Fuels: propane, butane, octane, JP-8, and diesel
- Duration: 700 hours to date
- Thermal cycles: 10
- Sulfur tolerance: 1000 ppm dibenzothiophene in JP-8

Pre-Reforming Evaluation

- CPOX as a baseline
- Evaluation of CPOX catalysts under ATR conditions
- Preliminary results indicate feasibility of operating CPOX as ATR

SOFC Operation on Hydrocarbon Containing Fuels

GE Hybrid Power Generation Systems



Concluding Remarks

- SECA system concept has been developed
- Current development efforts focus on resolving key technical issues concerning key system components
- Significant technical progress has been achieved in several technical areas