Solid Oxide Fuel Cell Manufacturing Overview

Hydrogen and Fuel Cell Technologies Manufacturing R&D Workshop

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Contents

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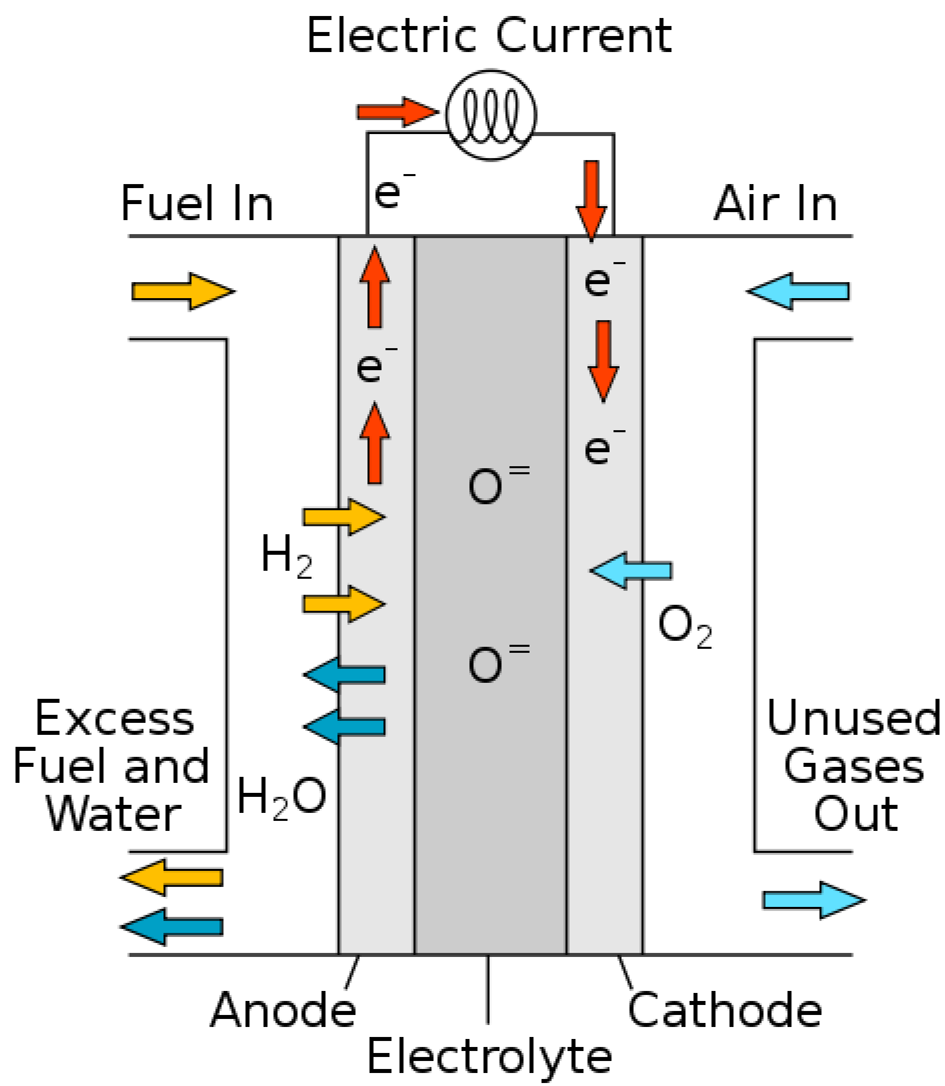
The Solid Oxide Fuel Cell Electrochemistry



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Stack Manufacturing Development

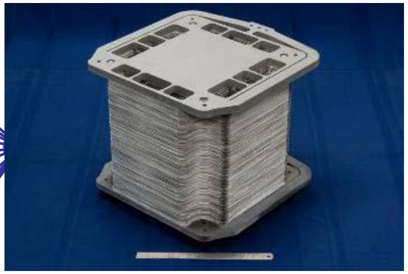
Component Development

Technology Development

- Cell
- Seal
- Interconnect
- Contacts
- Current Collection
- Flow Management
- Thermal Management
- Manufacturability
- Repeatability
- Tolerance

Stack Engineering Integration

Process Development and Piloting



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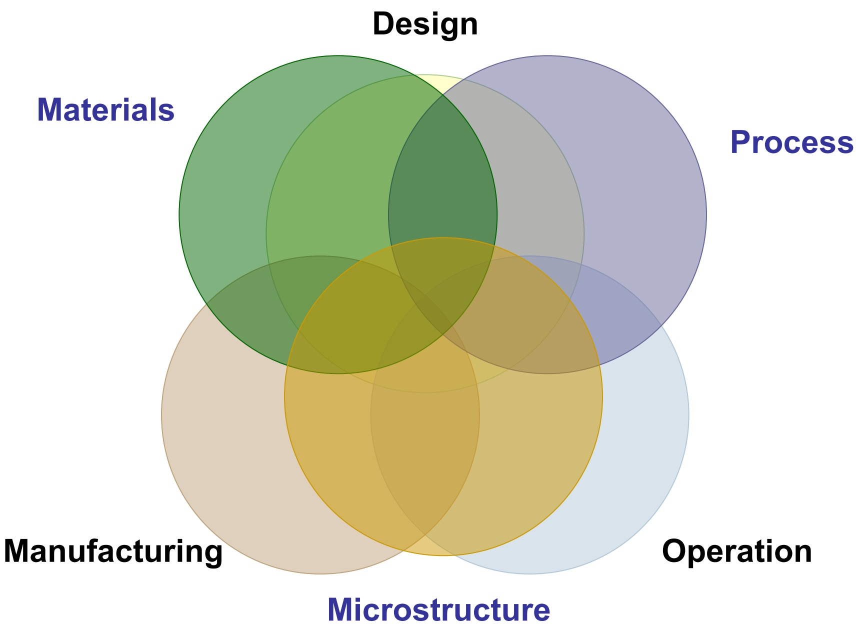
Influencing Factors

- Manufacturing
  - Selection of fabrication process
  - Evolution of desired microstructure
  - Cell-to-cell variability as manufactured (high yields necessary)
  - Stack (cell-to-cell variation)
- Design
  - Cell architecture
  - Stack design
  - Material stability
    - Oxidation behavior of steels
    - Sintering at operating conditions
    - Interdiffusion of cations
    - Phase changes/phase separation
    - Creep → warpage
- Operation
  - Fuel composition (Uf, H/C ratio, contaminants, f(t))
  - Oxidant (Uo, contaminants, pO_2)
  - Temperature (max)
  - Temperature gradient (°C/cm)
  - Temperature variation: x, y, z



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SOFC Elements: Independent of Construction

- Need to create and join the electrochemical elements (cells)
  - Anode, cathode, electrolyte
  - Ceramics
- Need to bring reactants to (and from) the cells and keep them where they belong
  - Flow fields, seals, manifolds
  - Ceramics or metallics
- Need to move electricity from cells
  - Interconnects, current collection
  - Ceramics or metallics
- Need to move heat from cells and stacks
  - Active and passive thermal management

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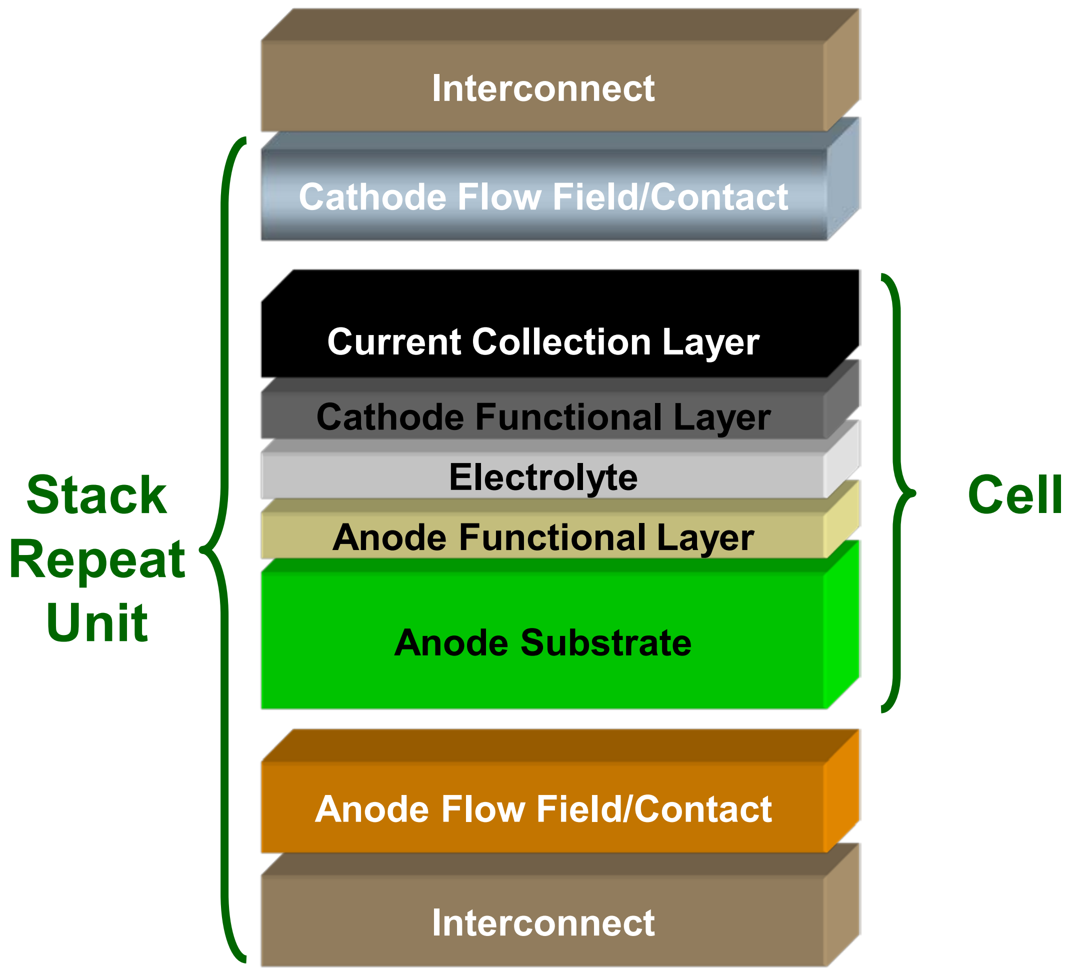
SOFC Stack Elements



- Fuel cell
  - Electrolyte, cathode, anode
- Interconnects
  - Deliver gases, transfer electrons, mechanically support cell
- Seals
  - Keeps gases where they belong
- Compression system
  - Hold it all in place
- Current collection
  - Get the electrons out

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Common Ceramic Manufacturing Steps

- Raw material preparation
  - Powder production
  - Powder preparation
  - Sizing
- Forming
  - Tape casting, slip casting, pressing, extrusion, calendaring, dispensing…
  - Printing, dip coating, spraying, vapor deposition…
- Conditioning
  - Drying, bisqueing, sintering

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Ceramic Raw Material Preparation

- Generally, most powders will be procured from suppliers
  - May require in-house processing such as sizing or purification
  - Inbound quality control
- Further preparation prior to forming or deposition
  - Additional functional materials may be added as well as binders or slurry agents
  - Milling is commonly used to refine and mix materials

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Ceramic Forming: Primary Layer

- Extrusion
  - Ceramic with a binder is forced through a mandrel forming the desired green shape (which can be closed at the leading end)
- Tape Casting
  - Ceramic tape is made by uniformly spreading slurry onto a smooth surface
- Drying
  - Both extrusions and tapes need to be dried to allow for handling and application of other functional elements prior to sintering
- Cutting
  - With extrusions, cutting may result in nearly no loss of material
  - In a planar cell, tape lost to cutting is a function of cell geometry and tape size
  - Recycling of tape lost to cutting is possible

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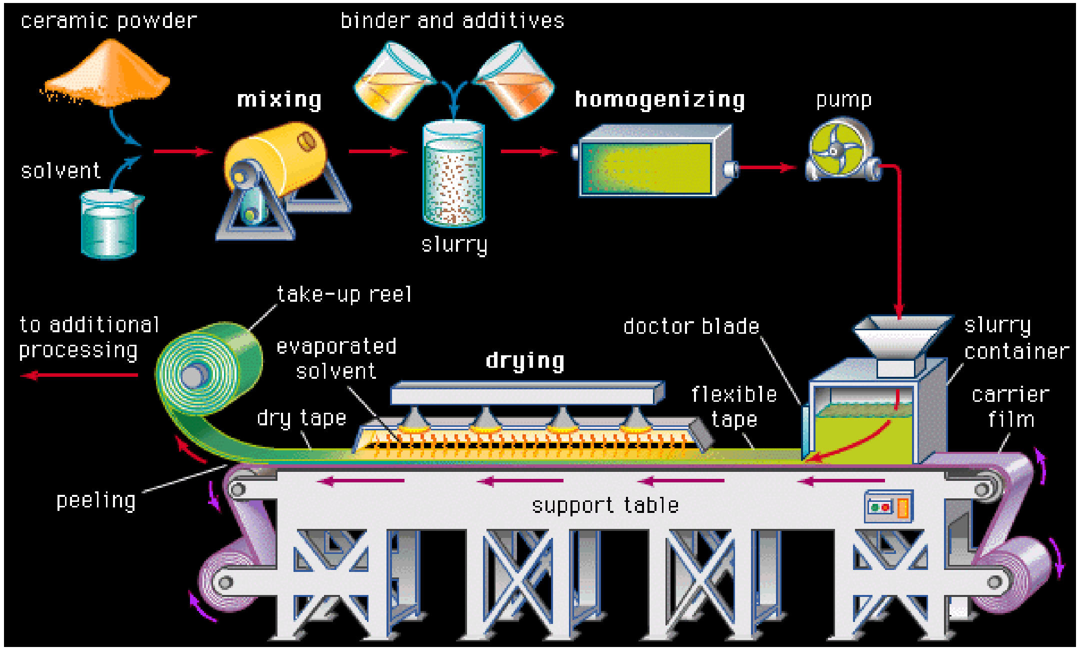
Tape Casting



Anode Tape

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Ceramic Forming: Additional Layers

- In either a planar or tubular configuration, additional layers are applied to the primary (usually support) layer
- Screen printing
  - Thickness can be limited, reasonable cycle times and cost, planar only
- Thermal spraying
  - Typically uses a flame or plasma, can provide thick coatings, higher depositions rates than vapor deposition
- Vapor deposition
  - Chemical processes use a fluid precursor which undergoes a chemical change at a solid surface, leaving a solid layer
  - Physical processes tend to require a low-pressure vapor environment to function properly
- Dip coating
  - Coating thickness a function of coated surface characteristics, ceramic paint properties, and number of applications
  - Equipment is inexpensive but cycle times can be relatively long

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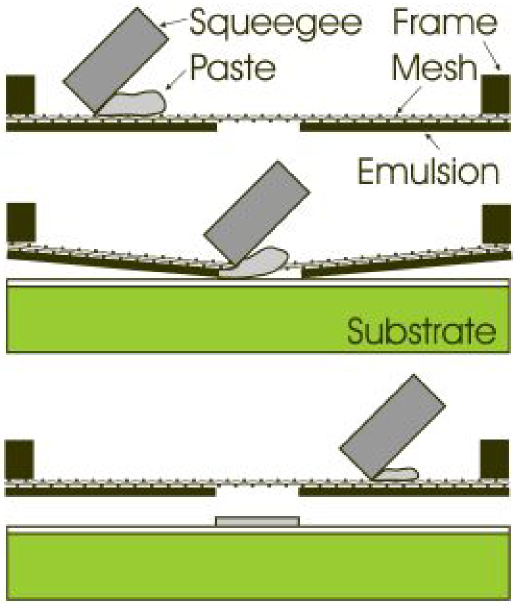
Screen Printing



Unfired Cell

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Ceramic Conditioning

- Drying
  - Typically done at temperatures up to a few hundred C
  - Yields a flexible green ceramic
- Bisque firing
  - 300 to 500 C
  - Yields a stable but brittle shape
- Sintering
  - Ceramic powders are partially melted allowing particles to partially fuse
  - Time and temperature dependent
- Co-firing is possible but varying shrinkage rates make it challenging
- Low volume production tends to use batch furnaces, continuous furnaces are available for high volume firing

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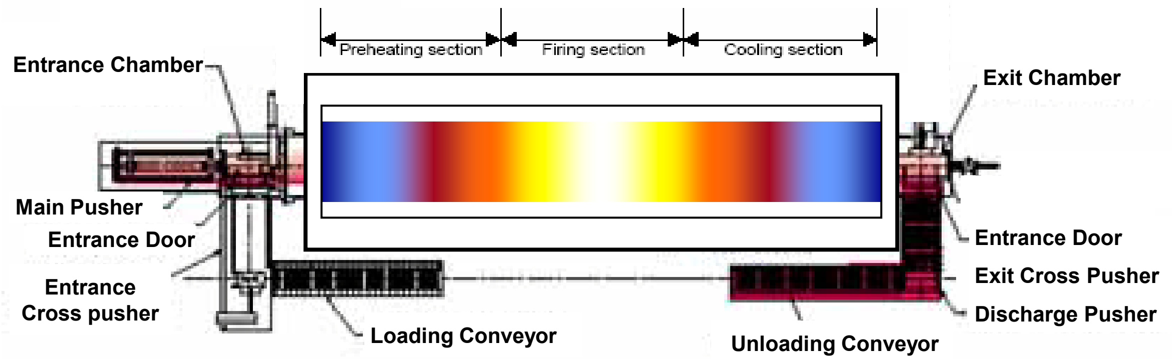
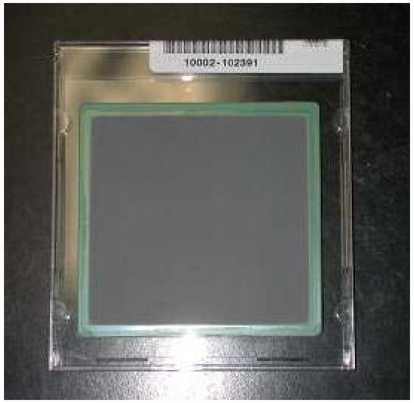
High Temperature Firing



Fired Cell



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Common Metallic Manufacturing Steps

- Metallic fabrication processes are well established and not unique to SOFC manufacturing
  - Stamping, punching, rolling, brazing, welding
  - Powder metallurgy, casting
- In some instances, coatings are applied to metallic stack components to improve oxidation characteristics

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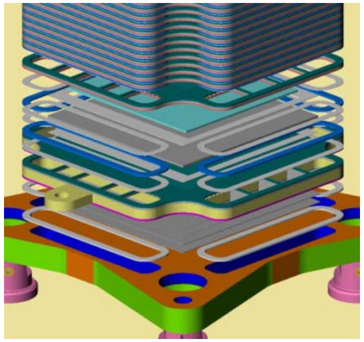
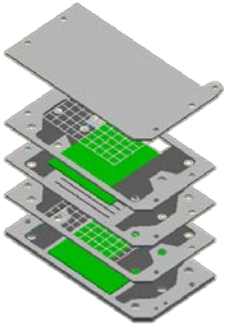
Assembly

- Planar
  - Layering of cells, flow fields, interconnects, seals, etc. bounded by end plates/manifolds and compressed
  - Leak check and initial conditioning
- Tubular
  - Tubes and interconnects assembled with manifolds and enclosed
  - Leak check and initial conditioning
- Automated assembly equipment can require significant volumes to justify its development and expense
- Conditioning and test equipment are nearly like full-featured development test stands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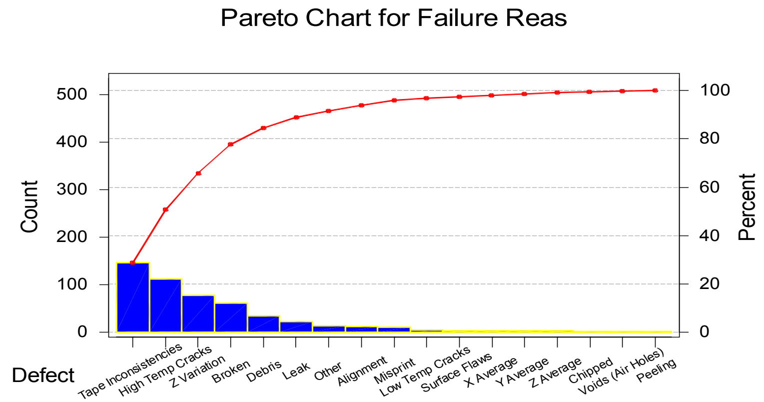
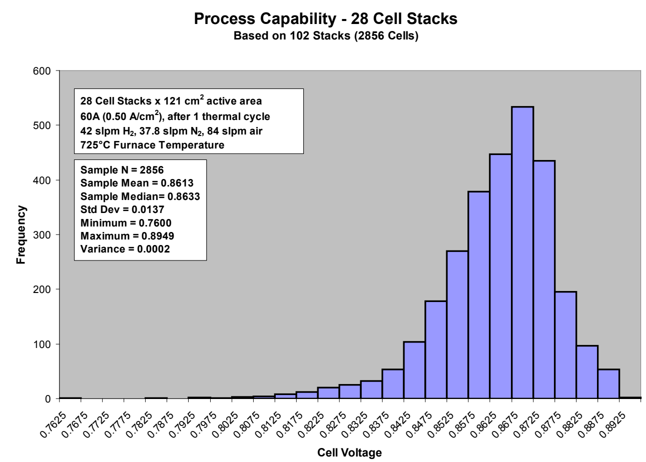
Quality Control

- Physical properties
  - Dimensions
  - Density or porosity
  - Flatness
  - Uniformity
  - Discontinuity
- Chemical properties
  - Compositions
  - Phases
  - Impurities
- Electrochemical properties



Defect	Tape Inconsistencies	High Temp Cracks	Z Variation	Broken	Debris	Leak	Other	Alignment	Misprint	Low Temp Cracks	Surface Flaws	X Average	Y Average	Z Average	Chipped	Voids (Air Holes)	Peeling
Count	146	112	77	61	34	22	14	12	10	4	3	3	3	3	2	2	1
Percent	29	22	15	12	7	4	3	2	2	1	1	1	1	1	0	0	0
Cum %	29	51	66	78	84	89	92	94	96	97	97	98	98	99	99	100	100



- **Some QC activities are amenable to automation on non-operating parts, others are not to either or both**

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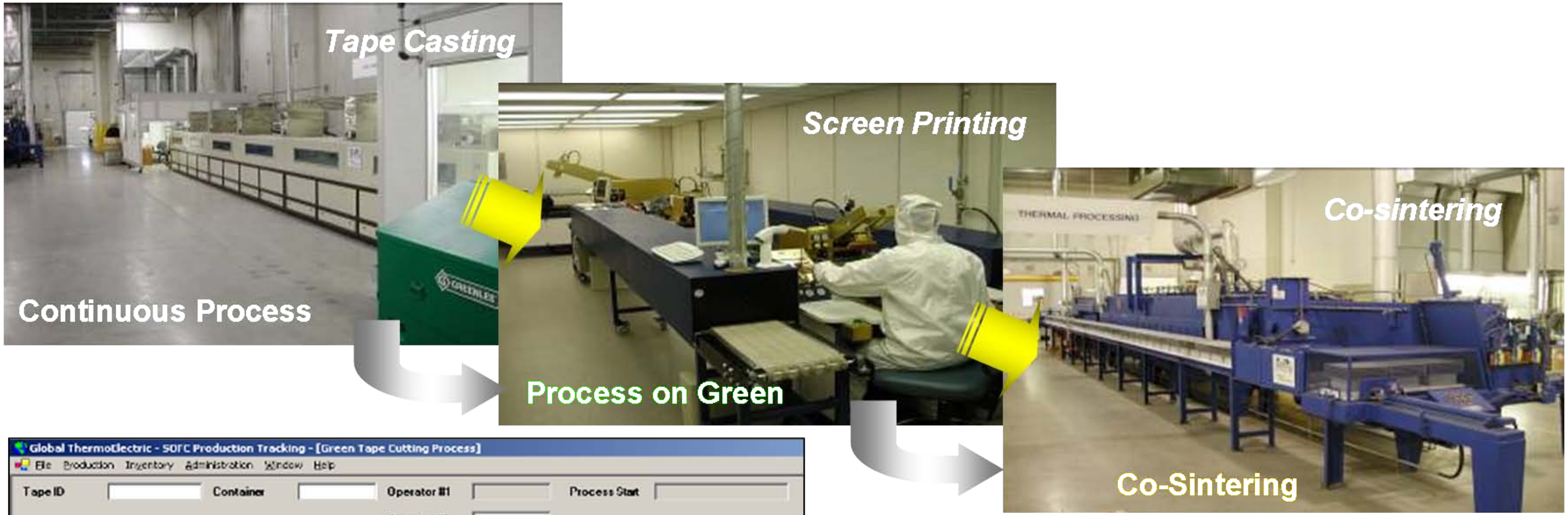
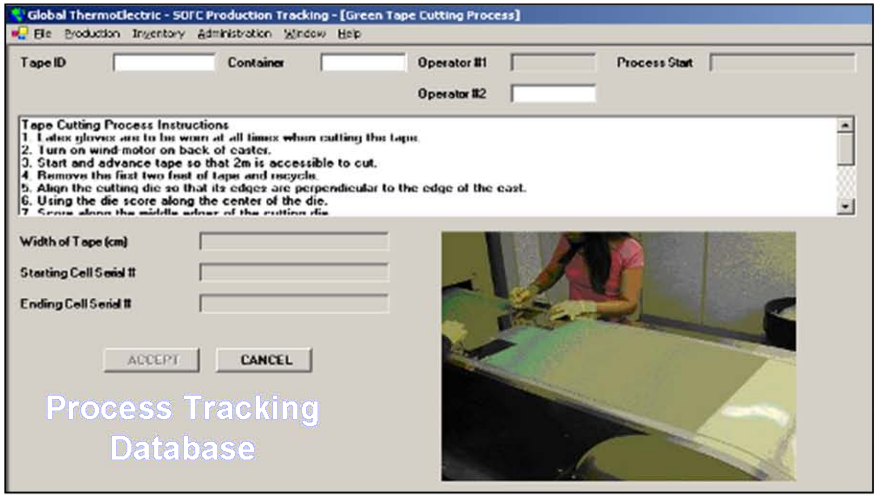
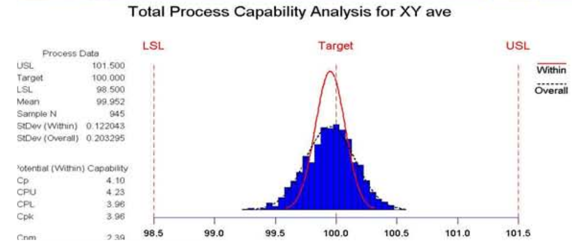
Cell Manufacturing Process Development







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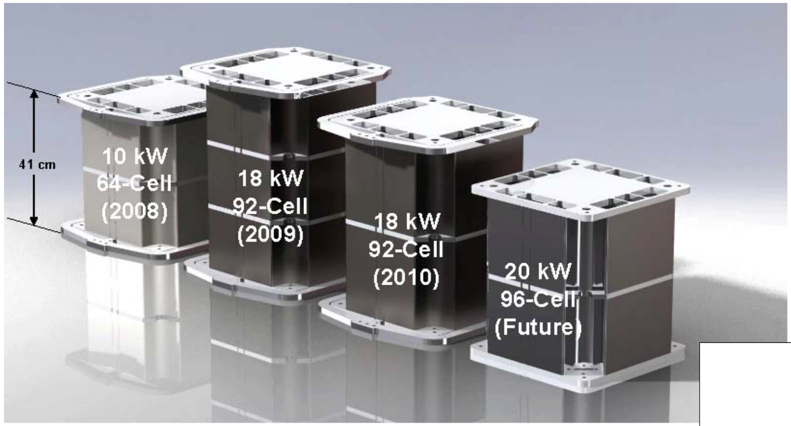
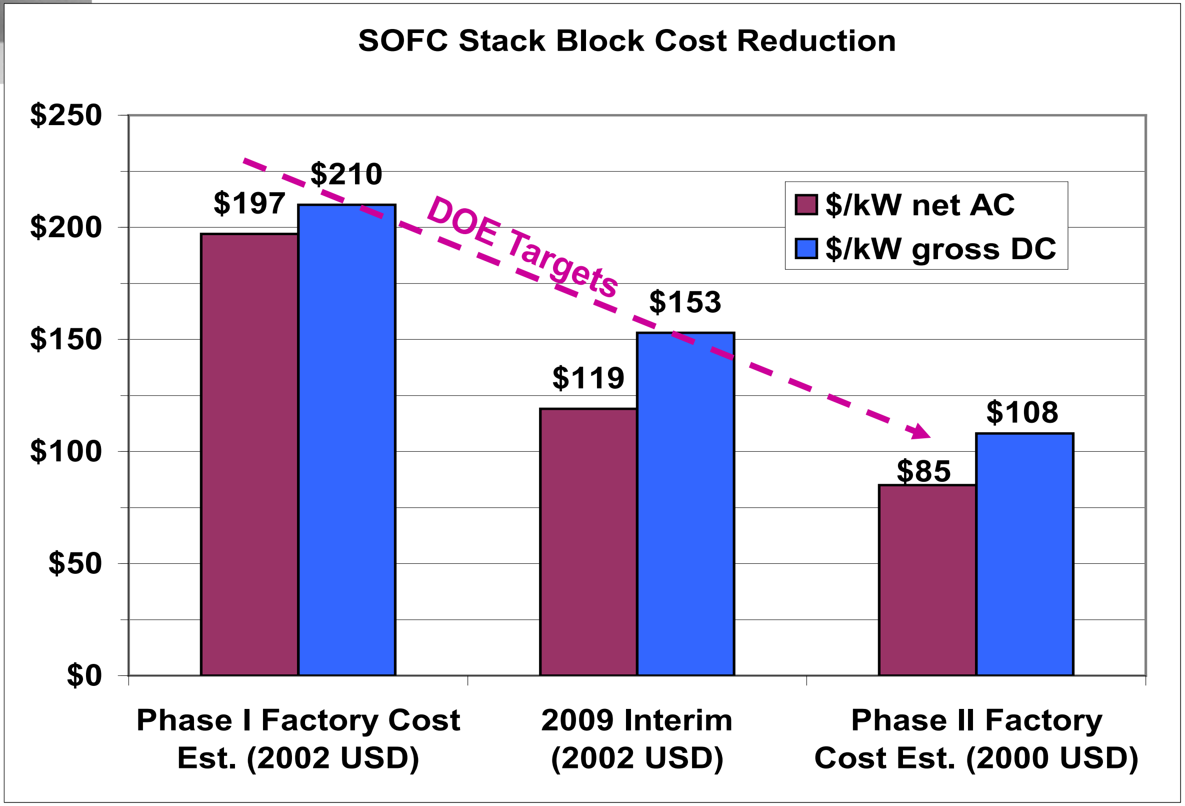
SECA Projected Stack Cost Reduction



The fuel cell stack cost has decreased substantially mainly due to the R&D activities in the SECA project



Cost Reduction Focus Areas

1. Stack Performance Increase
   - Peak Power Increase
     - Resolved thermal management issues
2. Material Reduction:
   - Thinner stack components
   - Interconnect material reduction
   - Reduced number of intermediate plates
3. Manufacturing Process Changes
   - Interconnect manufacturing development
   - Improved material utilization
4. Process Optimization
   - Automation
   - Elimination of process steps

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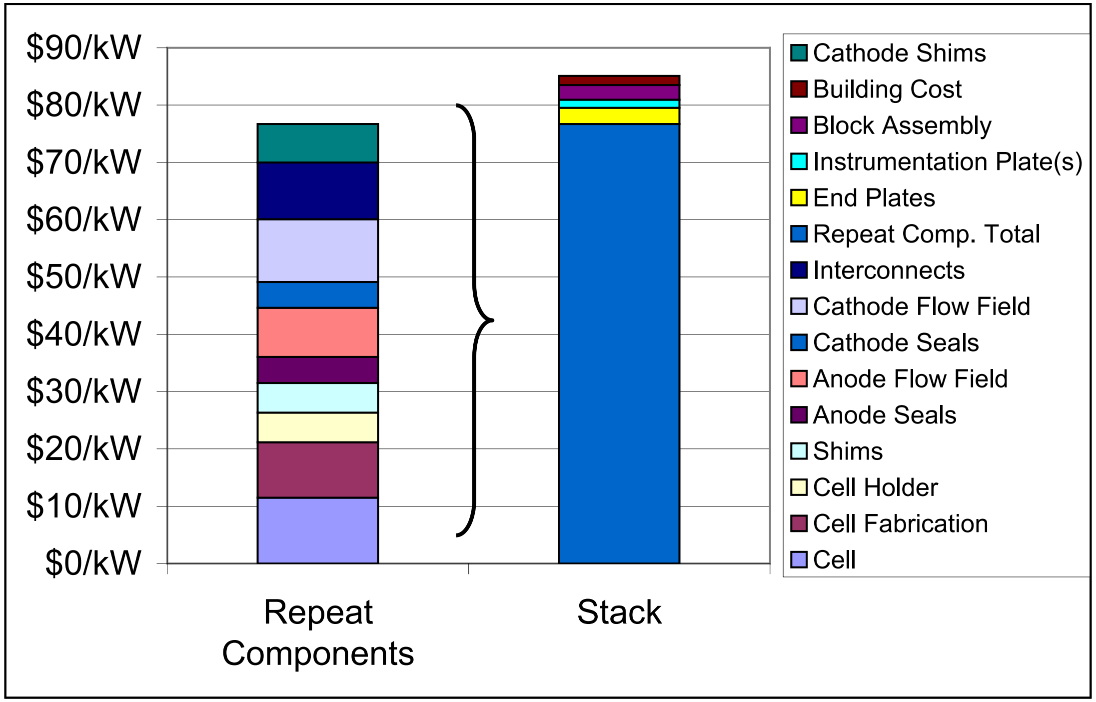
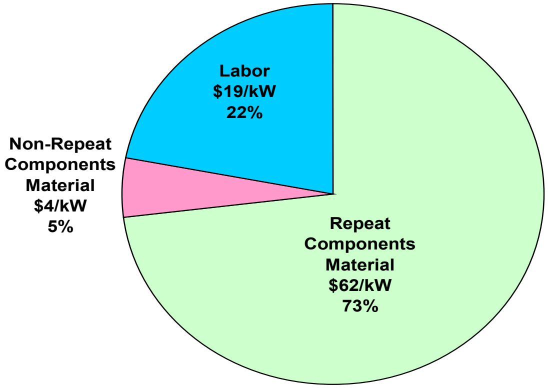
Stack Cost by Components and Category

96-cell Stack:
$2,658 (2000 USD)





- The majority of stack cost is driven by the cost of materials
- The relatively low labor cost is attributed partly to the fact that cells and seals are produced by VPS in-house

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Manufacturing Automation Strategies

- Manual operation
  - Production volumes from 5 MW to 25 MW
  - Use manual equipment with longer cycle times and smaller batch size
- Semi-automatic operation
  - Production volumes from 25 MW to ~100 MW
  - Use medium size equipment and has partial automation in key stations
- Automatic operation
  - High volume production from ~100 MW to 250 MW
  - Workstations and material handling system are automated

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Cost and Manufacturing Initiatives

- Materials
  - Materials reduction in cell and stack
  - Low cost materials
  - Interconnect coating
- Fabrication and assembly
  - Cell co-sintering
  - Sealing technology
- Quality control and testing
  - On-line QA/QC with real time feedback
  - Stack conditioning

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Questions?

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