Manufacturing Model: Simulating Relationships Between Performance, Manufacturing, and Cost of Production

SECA Modeling & Simulation Team - Integration Meeting

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1	Technical Issues
2	R&D Objectives and Approach
3	Activities for Phase I

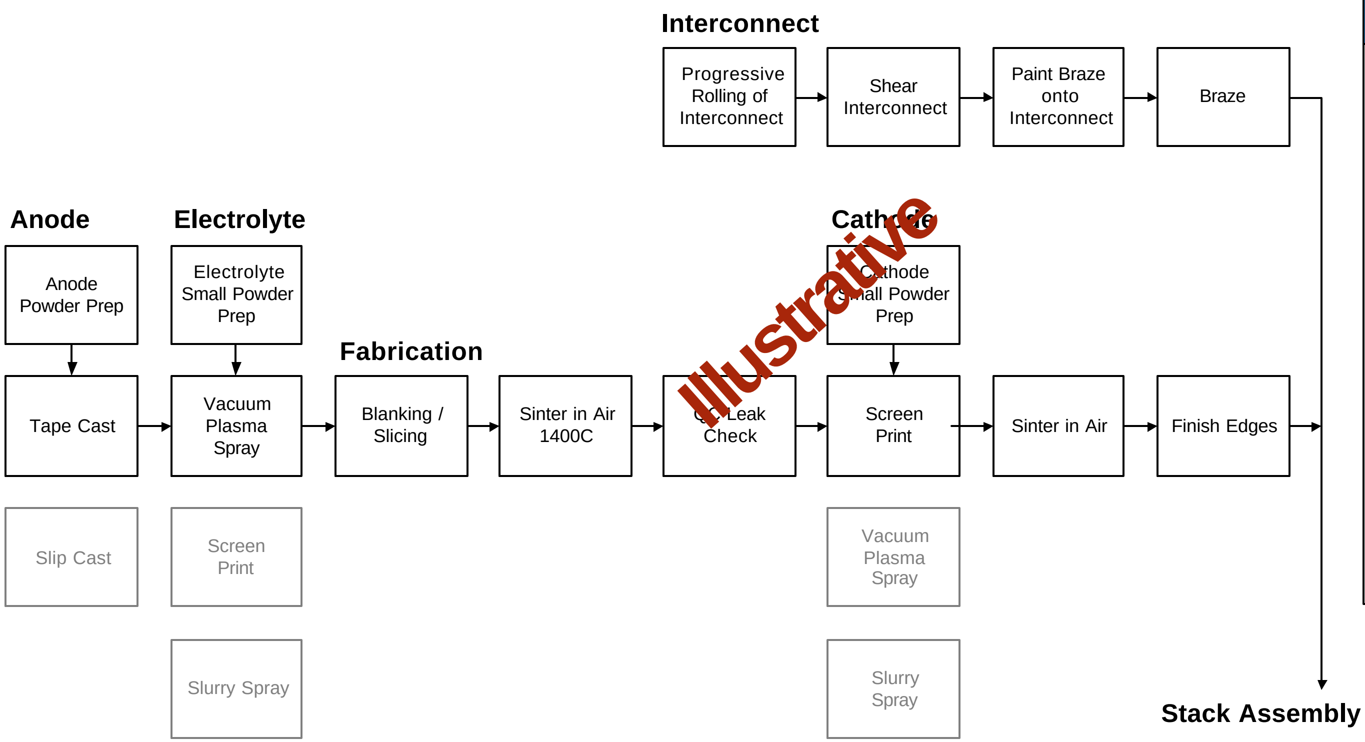
For commercial success, SOFC technologies must ultimately be manufacturable and cost competitive. A number of factors contribute to uncertainty at this time.

- Cell design, stack designs, and production processes are still in early stages of development
- SOFC stacks are radically different in structure from any currently mass-produced ceramic products
- Relationships between cell and stack design, design tolerances, and stack performance are not very well established

Proposed manufacturing processes may be amenable to high-volume production, however, specific processes and sequences must be selected.

Potential Process Flow for Planar Anode-Supported SOFC

Multi-Fired Process Flow



Note: Alternative production processes appear in gray to the bottom of actual production processes assumed

Process Flow Assumptions

- Electrical layer powders are made by ball milling and calcining.
- Interconnects are made by metal forming techniques.
- Automated inspection of the electrical layers occurs after sintering.

Relationships between cell and stack design, design tolerances, stack performance, and process yields are not very well established.

- Properties of individual layers - thickness, physical attributes, conductivity (electrical or ionic), polarization, transport, mechanical
- Manufacturing Options
  - Individual process steps
  - Sequence of steps
- Impact on
  - Process yield, tolerances, and reproducibility
  - Performance
  - Thermal cycling and Life
  - Cost

A state-of-the-art SOFC manufacturing model will allow developers and NETL to minimize the uncertainties inherently associated with commercialization of a new technology. The model must be able to:

- Handle all key SOFC stack components, including ceramic cells and interconnects
- Relate manufactured cost to product quality and likely performance, taking into account
  - manufacturing tolerances
  - product yield
  - line speed
- Address a range of manufacturing volumes, ranging from tens of MW to hundreds of MW per year
- Adapt to individual production processes under development by SECA industrial teams

1 Technical Issues

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3 Activities for Phase I

The Manufacturing Model Project will develop a tool to provide guidance to the DOE and SECA development teams on system design and manufacturing processes selection.

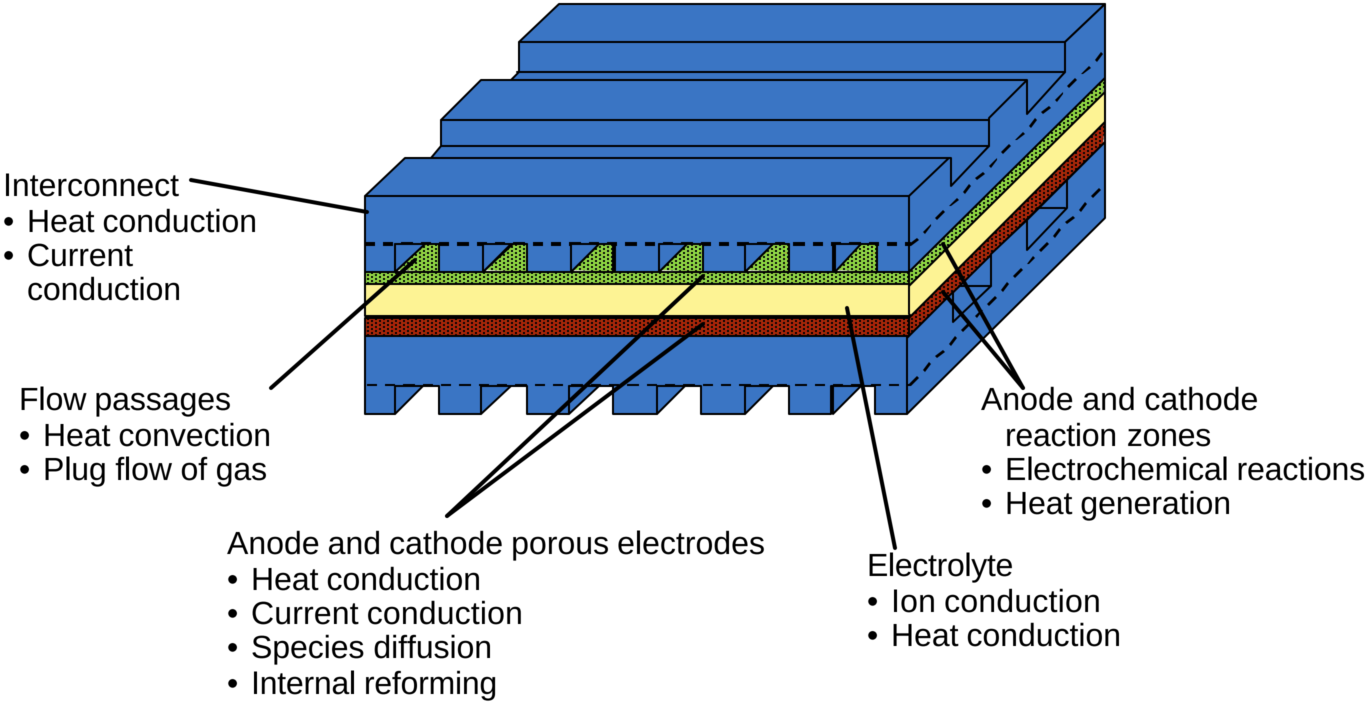
Objectives	◆ Develop model framework ◆ Demonstrate benefit of model for system development trade-off analyses ◆ Develop Phase 2 plan	◆ Expand Phase I model framework to other SOFC system designs, alternative materials, and manufacturing processes ◆ Incorporate findings and research of SECA teams
Deliverables	◆ Model framework ◆ Demonstration of model capabilities	◆ Workshop with SECA stakeholders

The primary output of the model will be an activity based manufacturing cost for various SOFC system scenarios.

Our approach to this assignment will leverage analysis models and experience gained through SOFC projects for NETL SECA and other clients.

- Anode-Supported Planar SOFC Detailed Manufacturing Cost Assessment
- Assessment of Status of Residential Fuel Cell Developments (for EPRIsolutions)
- Scale-up Study of 5-kW SECA Solid Oxide Fuel Cell Modules: 250-kW system
- Conceptual Design of POX/SOFC Auxiliary Power Unit (APU) 5kW System
- Technology Assessment of Solid Oxide Fuel Cell Stack Technology (for EPRIsolutions)
- Assessment of Structural Limitations in the Scale-up of Anode Supported SOFCs

The structural model accounts for all the relevant electro-chemo-thermo-mechanical phenomena, which influence cell performance (hence cost).

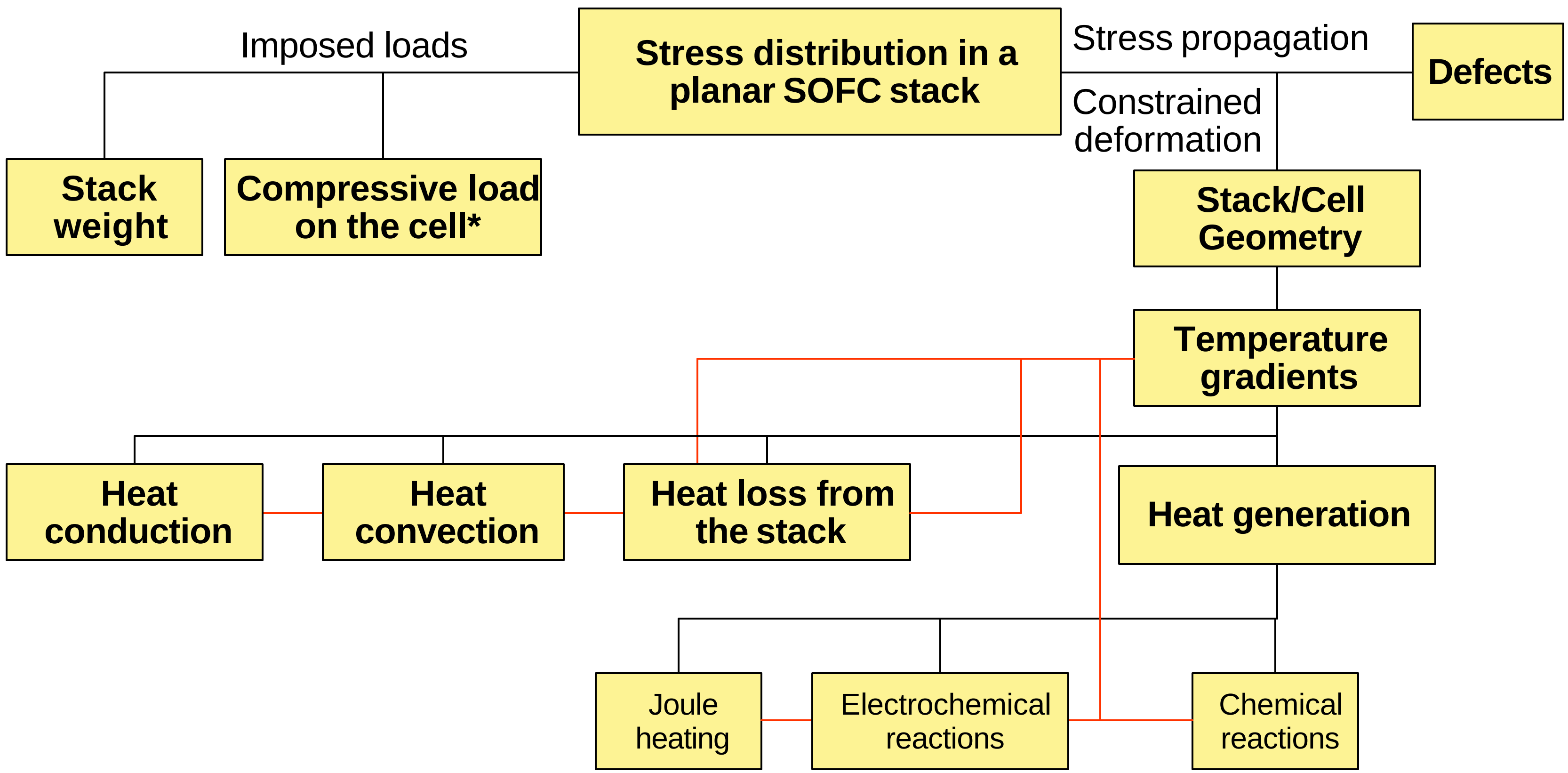


Solution of equations for:

- Energy conservation
- Mass conservation
- Charge conservation

→ **Temperature gradients in the cell during operation** → **Mechanical stress distribution during operation** ← **Constraints**

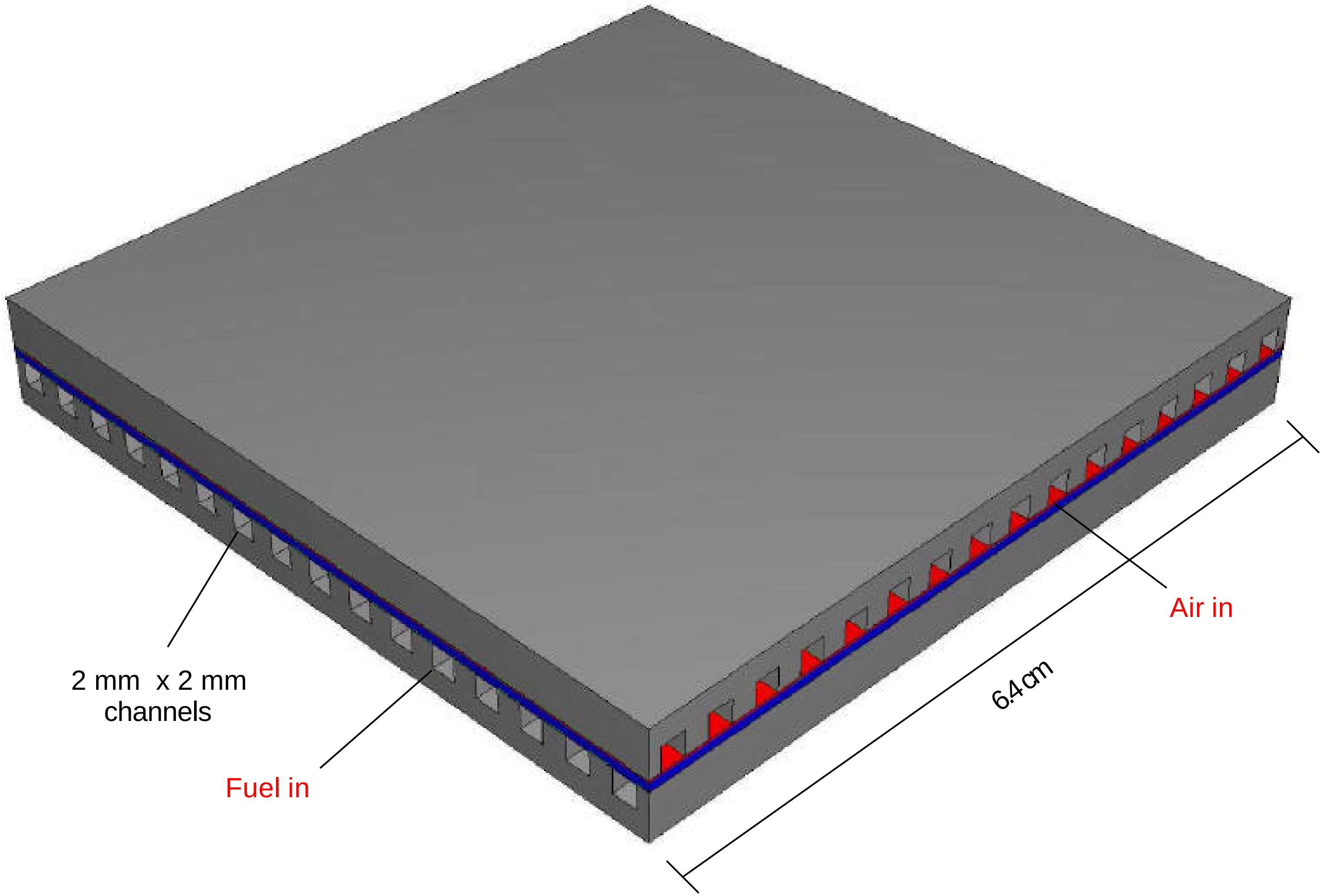
The mechanical stress distribution in a planar SOFC is governed by a combination of design parameters and operating conditions.



* necessary for sealing and electrical interconnection in many planar stack designs

The non-linear interactions among these phenomena make purely empirical characterization impractical and one-by-one analysis difficult.

To evaluate the impact of cell size, we use a cross-flow configuration.



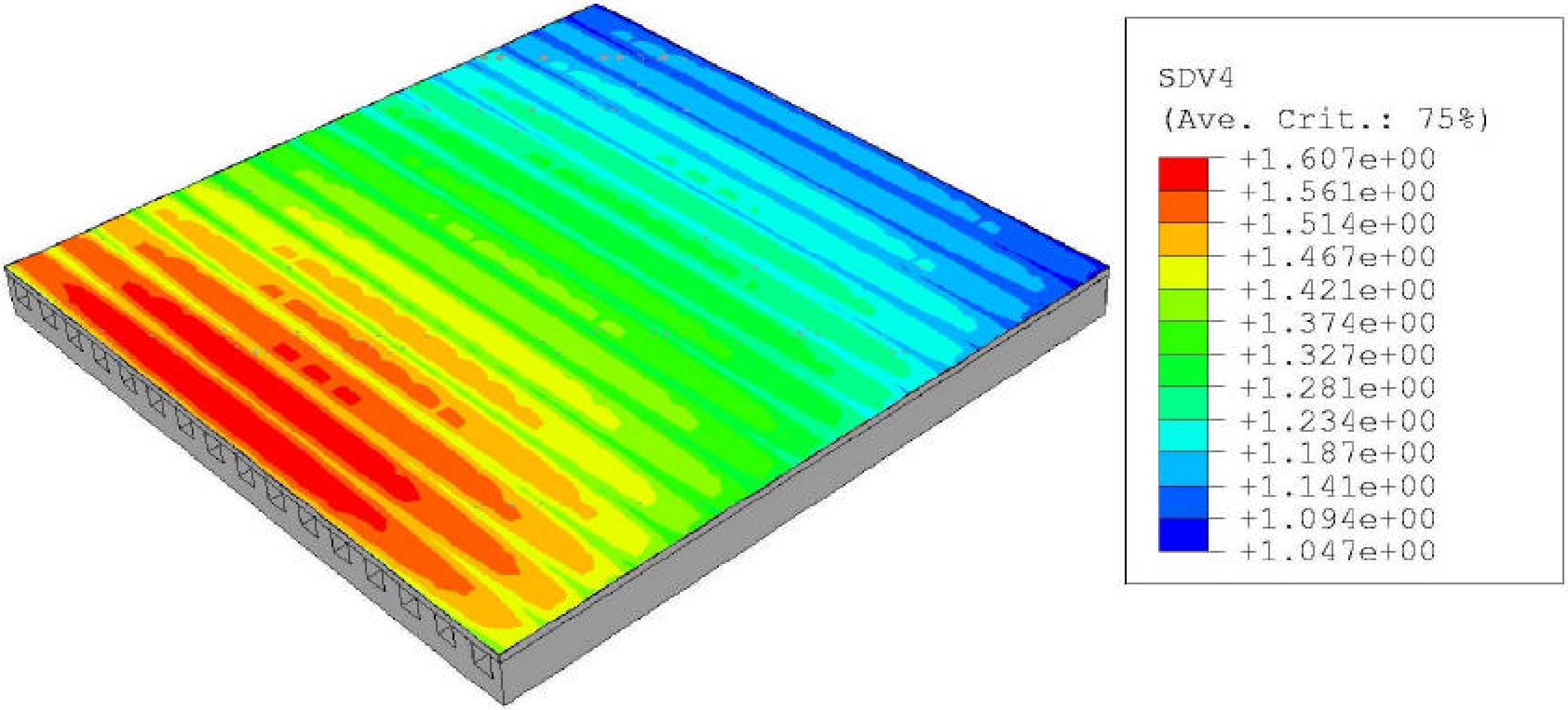
We are currently developing a similar model for circular cells.

For the base case, we selected operating conditions consistent with previous TIAX studies.

Parameter	Value
• Cell voltage	• 0.7 V
• Composition of the reactant streams	• Anode: 97 % H_2, 3 % H_2O, Cathode: air
• Gas inlet temperatures	• 650 °C at the Anode and Cathode
• Fuel utilization	• ~ 50 %
• Cathode stoichiometry	• ~ 5, the cathode flow rate was adjusted such that the temperature at the cell outlet was nominally 800 °C.

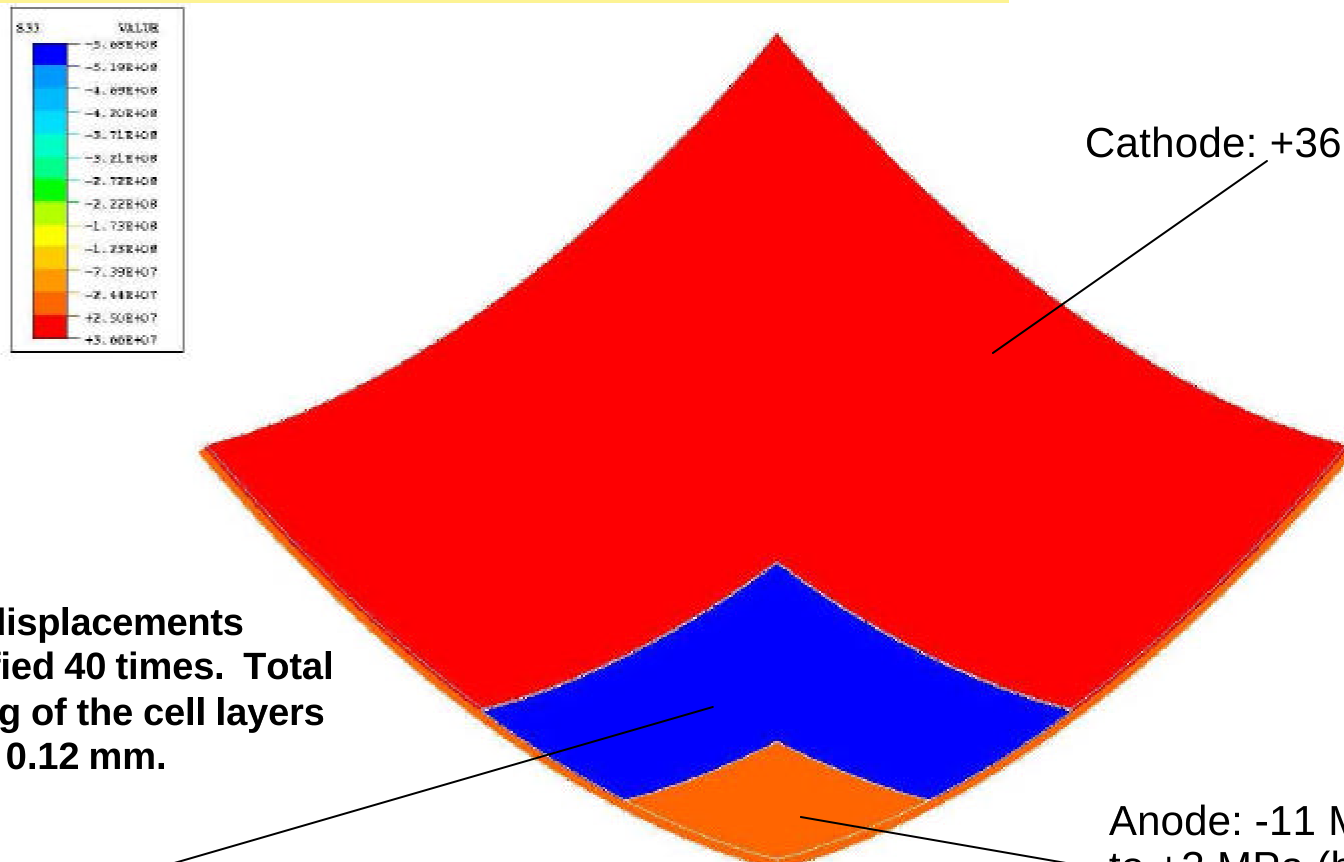
The structural model calculates the time-dependent current density distribution during cell operation.

Cell voltage = 0.7 V
Steady state current density distribution, average = 1.3 A/cm^2



Uncompensated bending stresses lead to warping of the MEA when it is cooled down to room temperature from the sintering temperature.

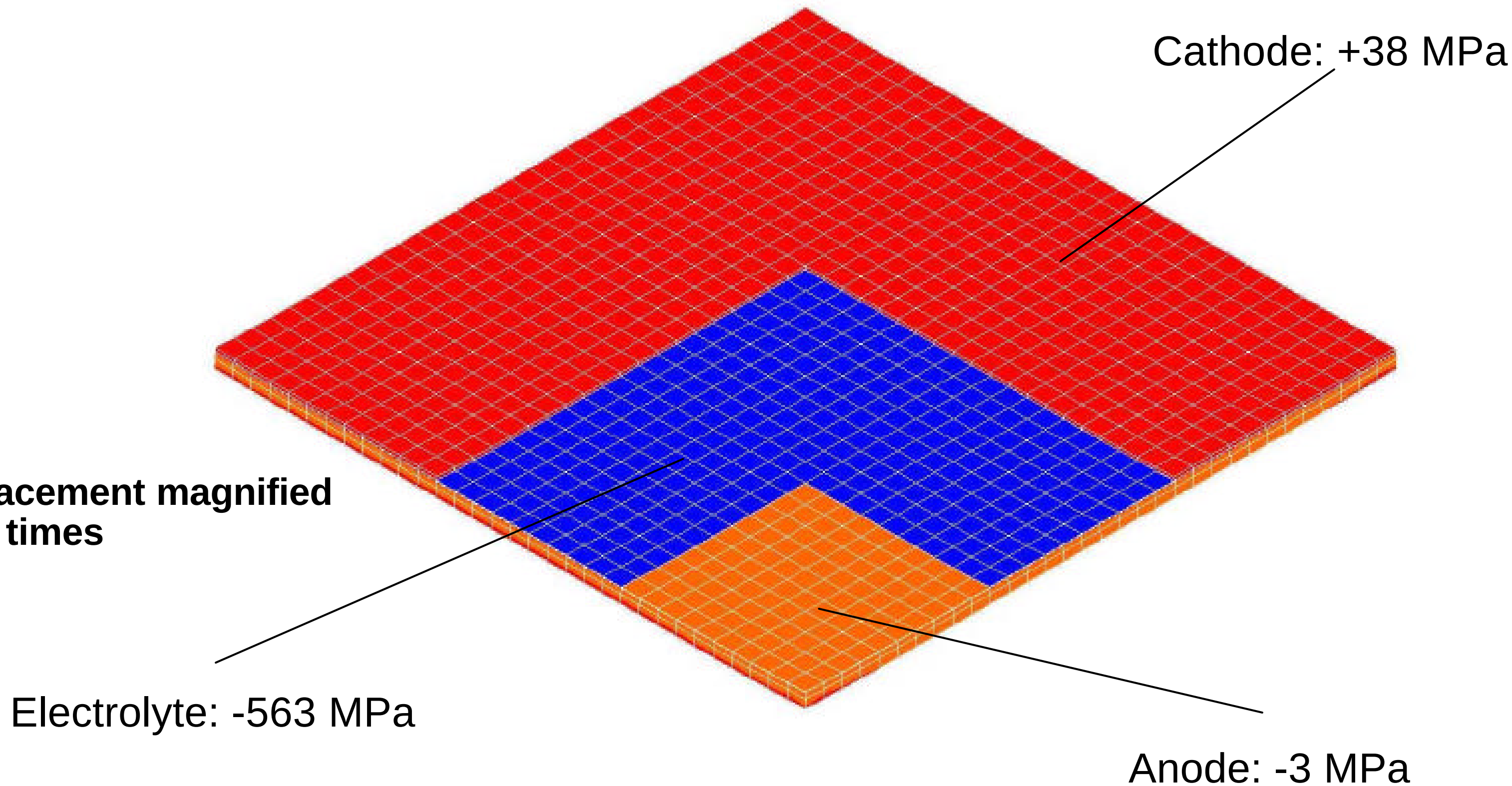
Residual stresses and warping in the ceramic layers at room temperature



Note: displacements magnified 40 times. Total warping of the cell layers equals 0.12 mm.

A confining pressure (0.4 MPa) flattens the MEA and removes the anode bending stress but does not alter the cathode or electrolyte stresses.

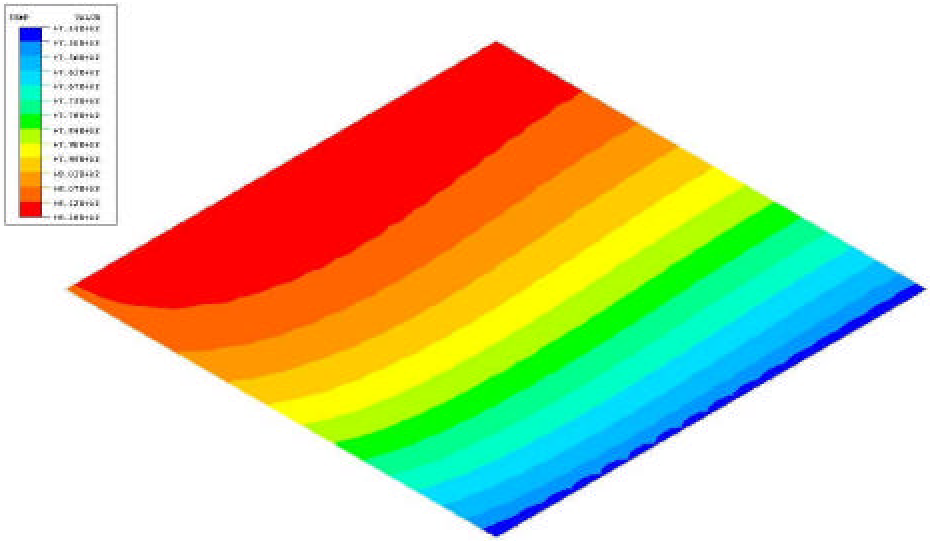
Stress in the ceramic MEA layers after 'flattening' between interconnects at room temperature



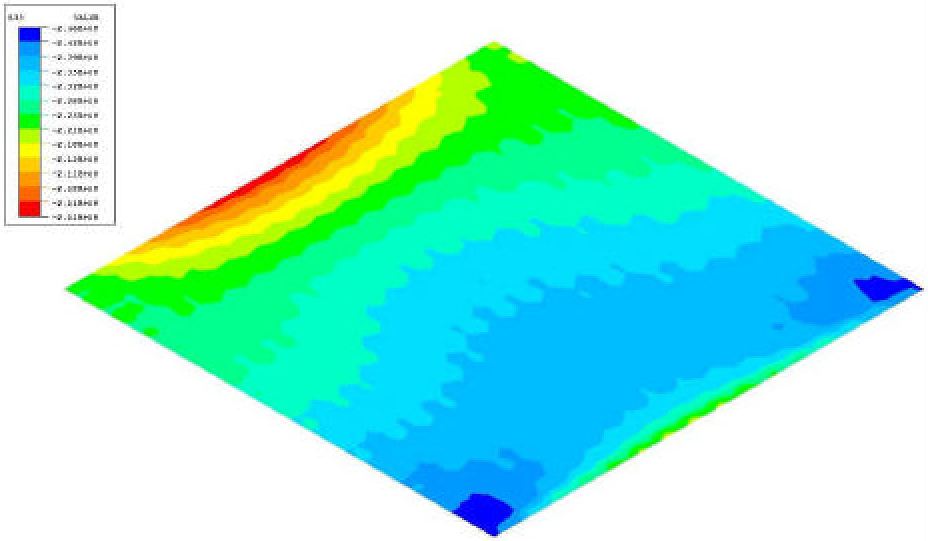
Displacement magnified by 40 times

Applying the steady state temperature profile shows that the stress distribution is much less severe than at room temperature.

Electrolyte temperature varies from 744 °C (blue) to 818 °C (red) for operation at 0. 7 V



Electrolyte stress varies from -246 MPa (blue) to -201 MPa (red) for operation at 0. 7 V



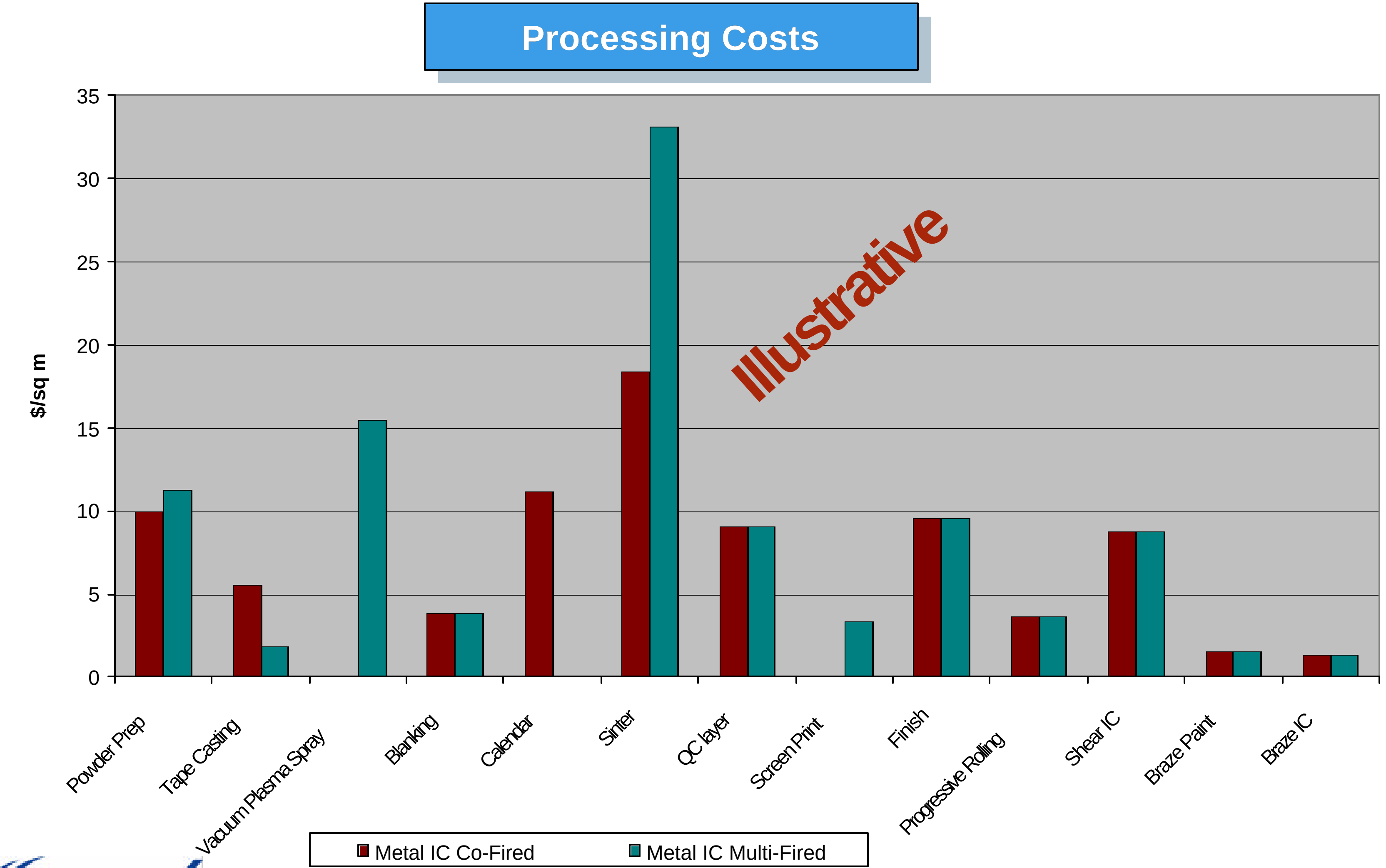
For a given process flow and production volume, assumptions or data must be developed for each process step.

Illustrative

Process Description	Equipment Description	Equipment Cost	Cycle Time (mins)	Reject & Scrap (%)	Number Laborers per Station	Tool Cost ($)
Automated Tape Casting	Tape caster	$300,000	0.0004	0.0%	0.2	
Tile QC Vacuum Leak Test	Inspection Machine	$300,000	0.17	20.0%	1	
Vacuum Plasma Spray	Vacuum plasma gun	$1,200,000	1.00	2.0%	0.25	
Screen Print	Manual station	$20,000	0.02	1.0%	1	$100
Diamond Grind Stack Edges	Blanchard grinder	$300,000	30.00	5.0%	1	$2,000
IC Progressive Rolling	Yoder M mill	$130,000	0.00	3.0%	1	$12,100
IC Shear	Shear + flying die	$55,000	0.01	2.0%	1	$15,000
IC joining -- paint	Paint gun	$10,000	0.10	0.0%	0.2	
IC joining -- heat treat	Brazing furnace	$400,000	180.00	5.0%	0.2	
Stack Calendar	Press + heated dies	$20,000	0.50	1.0%	1	$15,000
Roll Calendar	Roll calendar	$60,000	0.04	1.0%	0.2	
Blanking / Slicing	Press + heated dies	$150,000	0.17	1.0%	1	$30,000
Continuous Sinter in Air 12 hrs	Sintering Furnace	$500,000	720.00	2.0%	0.2	
Weigh Powders	Weigh Scales	$5,000	30.00	0.0%	0.2	
Ball Milling	Ball Mills	$22,000	300.00	2.0%	0.2	
Calcine	Calciner	$90,000	720.00	15.0%	0.2	
Air Classification	Air Classifier	$100,000	1.00	5.0%	0.2	

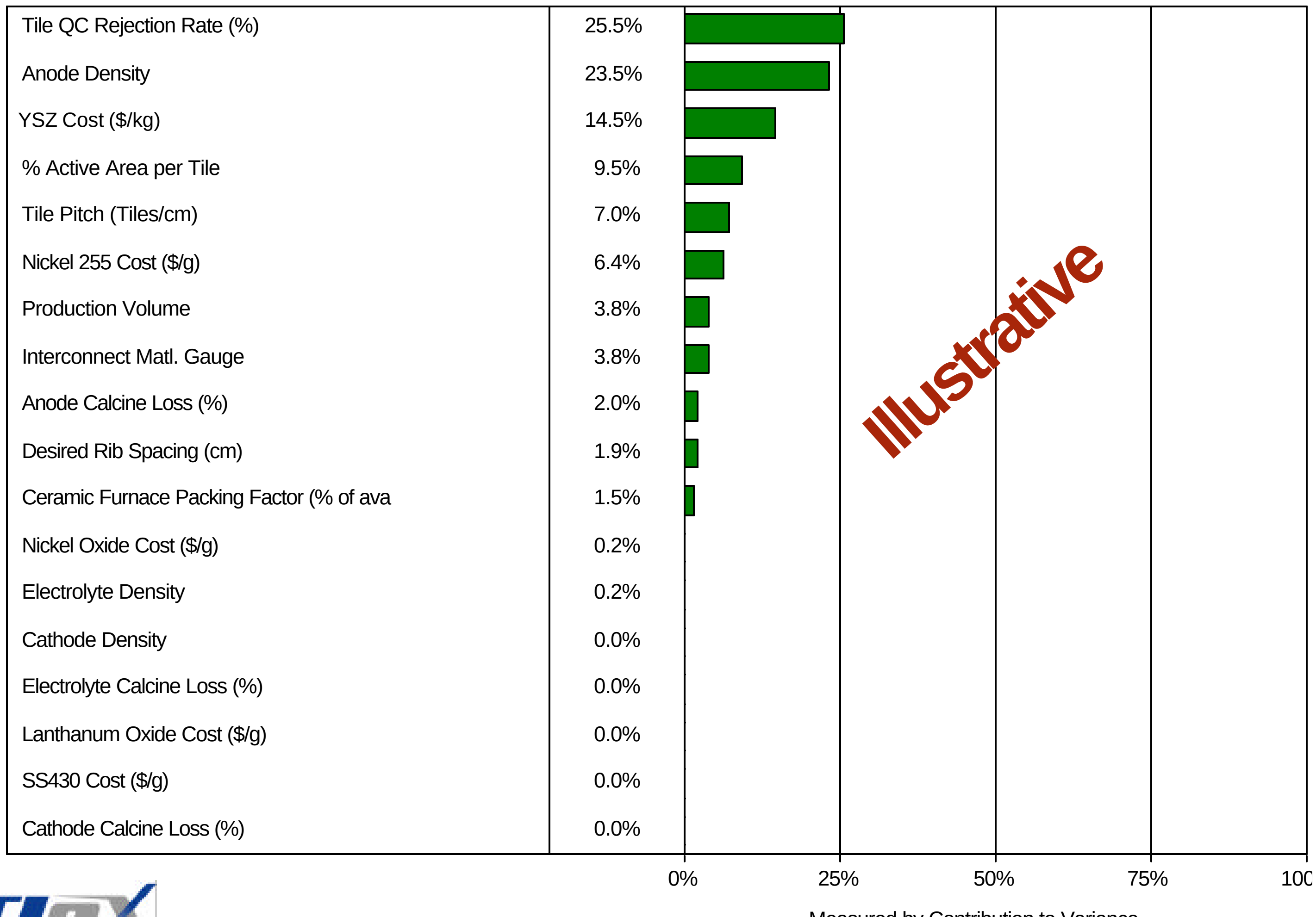
The impact of design decisions, e.g. layer thickness, on these assumptions and cost will be assessed.

The cost implications of different process options will be considered.



The major cost drivers for different processing and design scenarios will be compared.

Sensitivity Chart — Target Forecast: Co-Fired Metal Planar Cost



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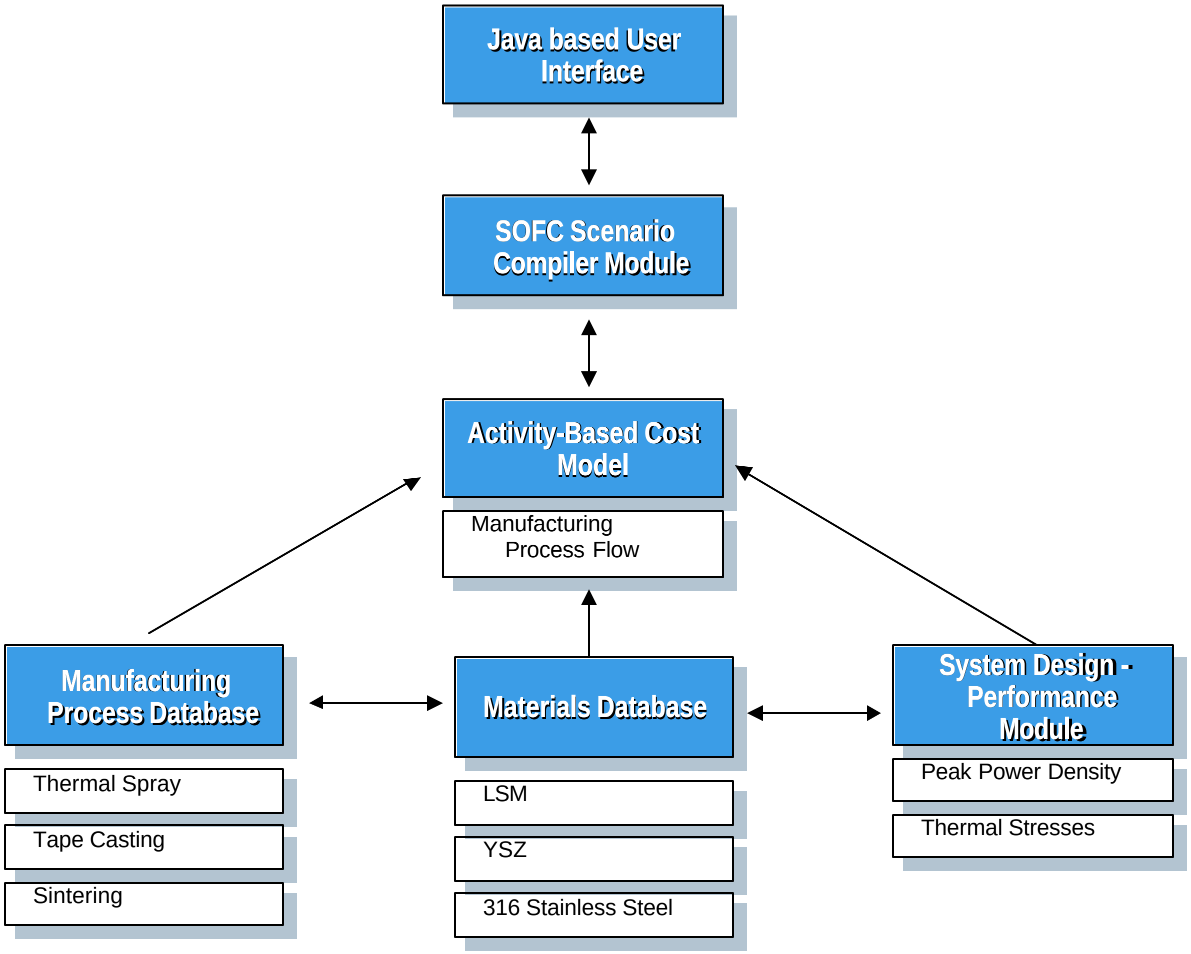
Phase I will be conducted in three tasks.

Objectives	◆ Develop architecture of manufacturing model ◆ Review architecture with SECA stakeholders	◆ Revise existing model architecture based on Task 1 workshop ◆ Demonstrate manufacturing model with baseline SOFC system	◆ Report project progress ◆ Prepare Phase I report that summarizes critical manufacturing steps and performance parameters ◆ Define Phase II development effort
Deliverables	◆ Workshop with SECA stakeholders ◆ Definition of model framework, user interface with model, and critical issues to be assessed, model assumptions	◆ Workshop with SECA stakeholders	◆ Monthly updates ◆ Phase I final report

In Phase I, we will build on an activity-based cost model developed in an earlier NETL program.

Workshop Discussion Issues:

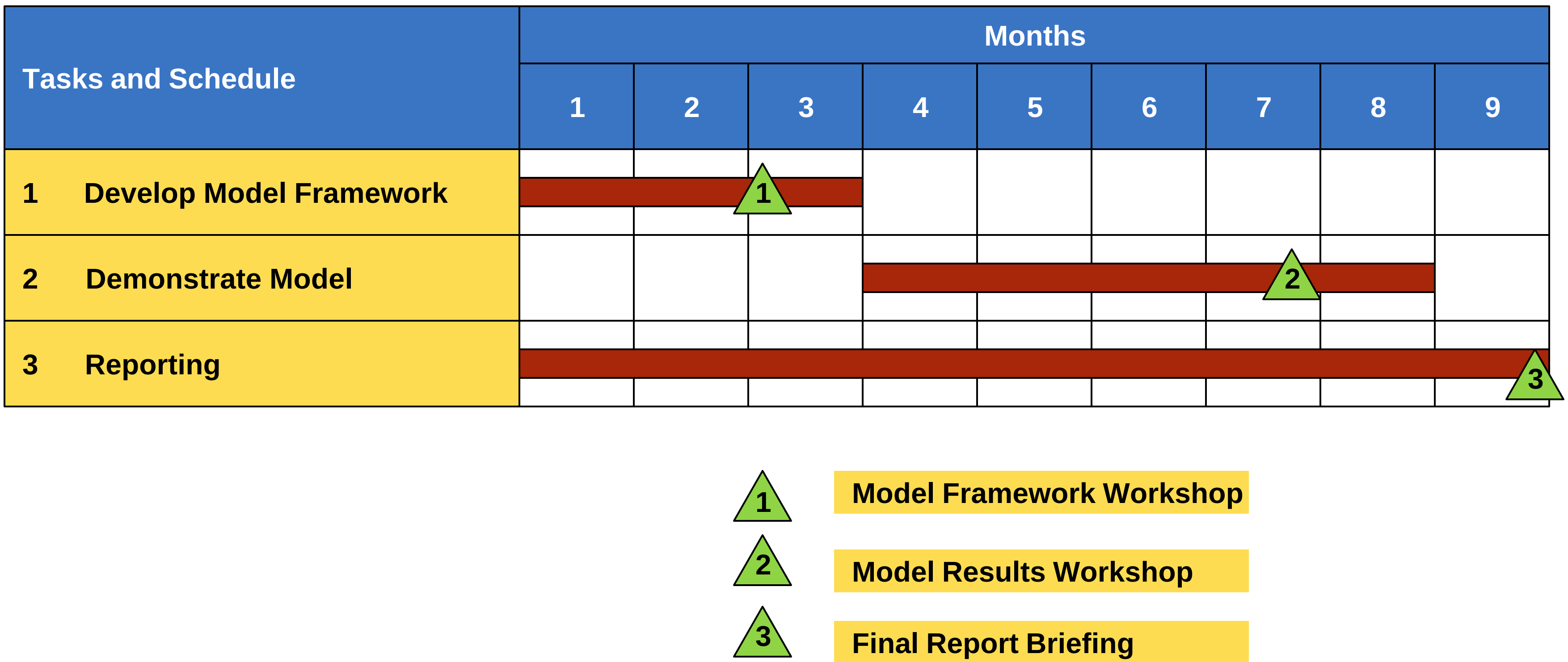
- Protection of individual SECA team proprietary information
- Security of User Interface
- Access to model
- Access to process and equipment data and specifications



We anticipate that we will provide DOE and industrial teams with some key conclusions and recommendations:

- Identification of critical manufacturing steps and performance parameters
  - if considerable uncertainty exists about these steps, specific additional SECA R&D objectives may be developed
- Refinement of SECA technology cost and performance estimates
- Definition of desirable next steps

We expect Phase I to be completed in approximately nine months, according to the schedule presented below.



The TIAX core team consists of five members whose backgrounds are particularly appropriate to this project.

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