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

SECA Core Technology Program Workshop

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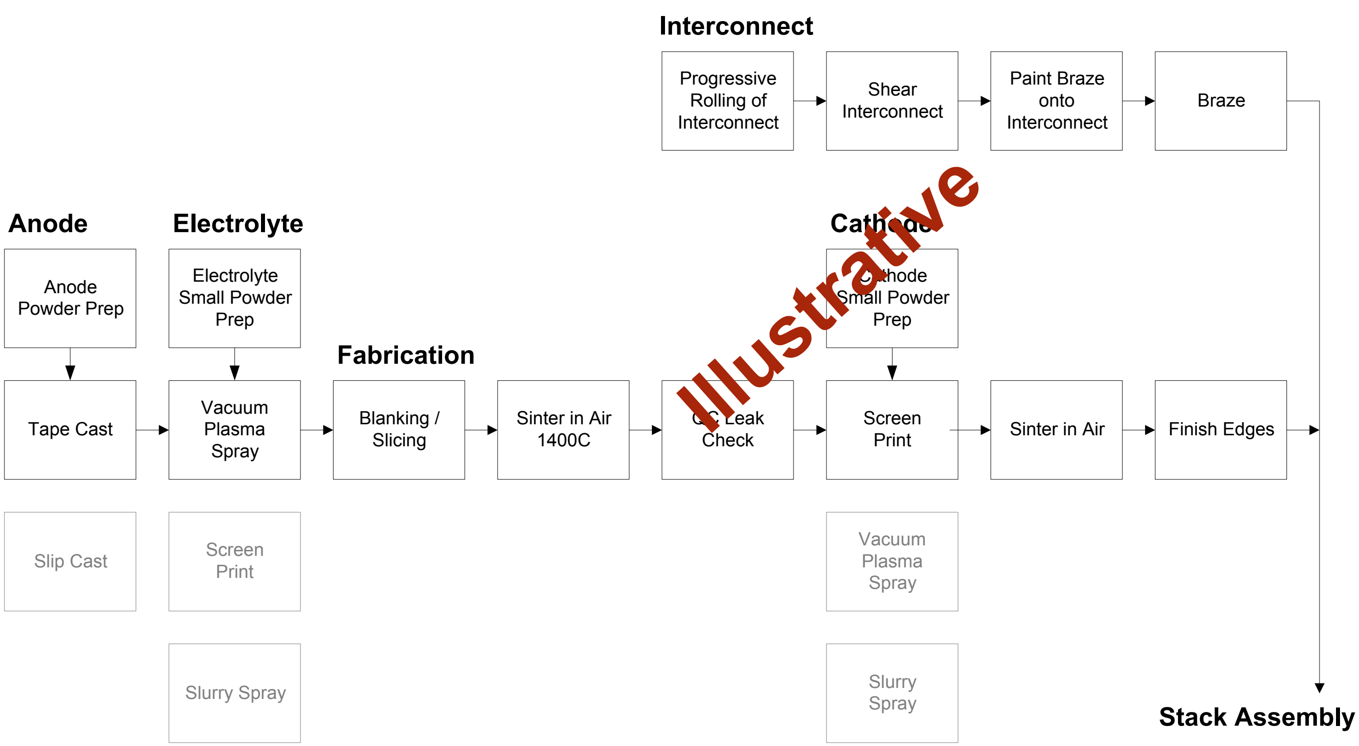
For commercial success, SOFC technologies must ultimately be manufacturable and cost competitive. A number of factors contribute to uncertainty at this time.

- 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, e.g., physical attributes, conductivity (electrical or ionic), polarization, transport, mechanical, are not well defined as a function of temperature
- 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

2 R&D Objectives and Approach

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.

	Phase I SOFC Manufacturing Model Framework and Demonstration	Phase 2 SOFC Manufacturing Model Expansion and Use
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.

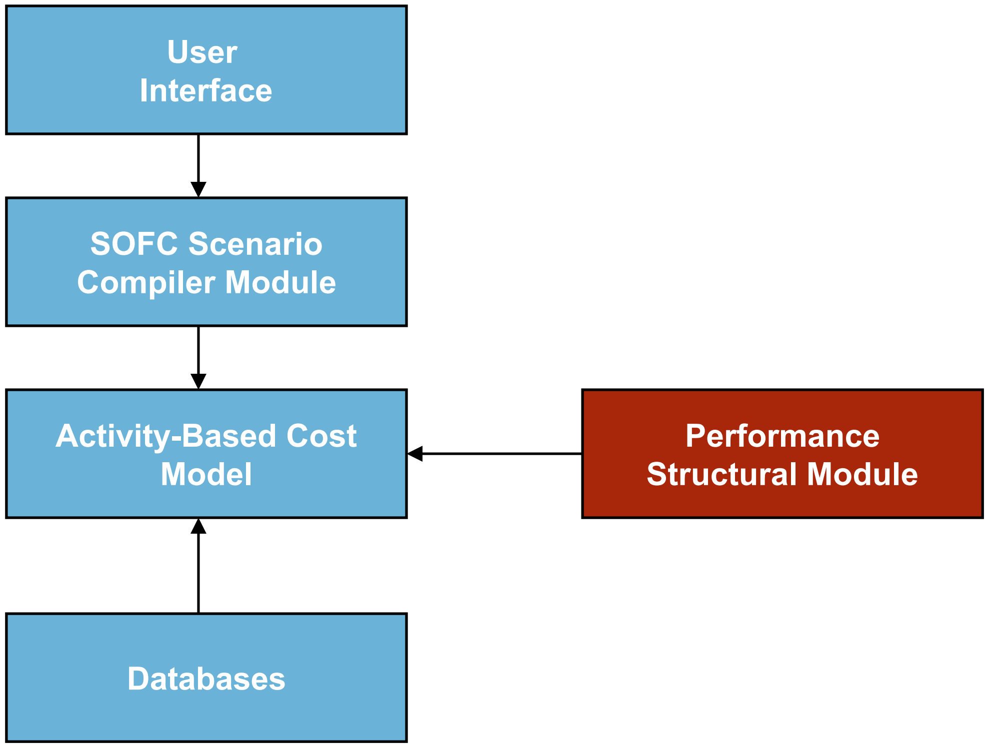
Phase I will be conducted in three tasks.

	Task 1 Model Framework Development	Task 2 Model Demonstration	Task 3 Reporting
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

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

The cost model will be augmented with a SOFC performance model to help relate manufacturing quality to performance.



The model uses a set of databases to calculate cost for defined production (process flow) scenarios and performance assumptions.

Inputs
- Design
- Performance Parameters
- Manufacture Processes and Flow
- Production Scenarios

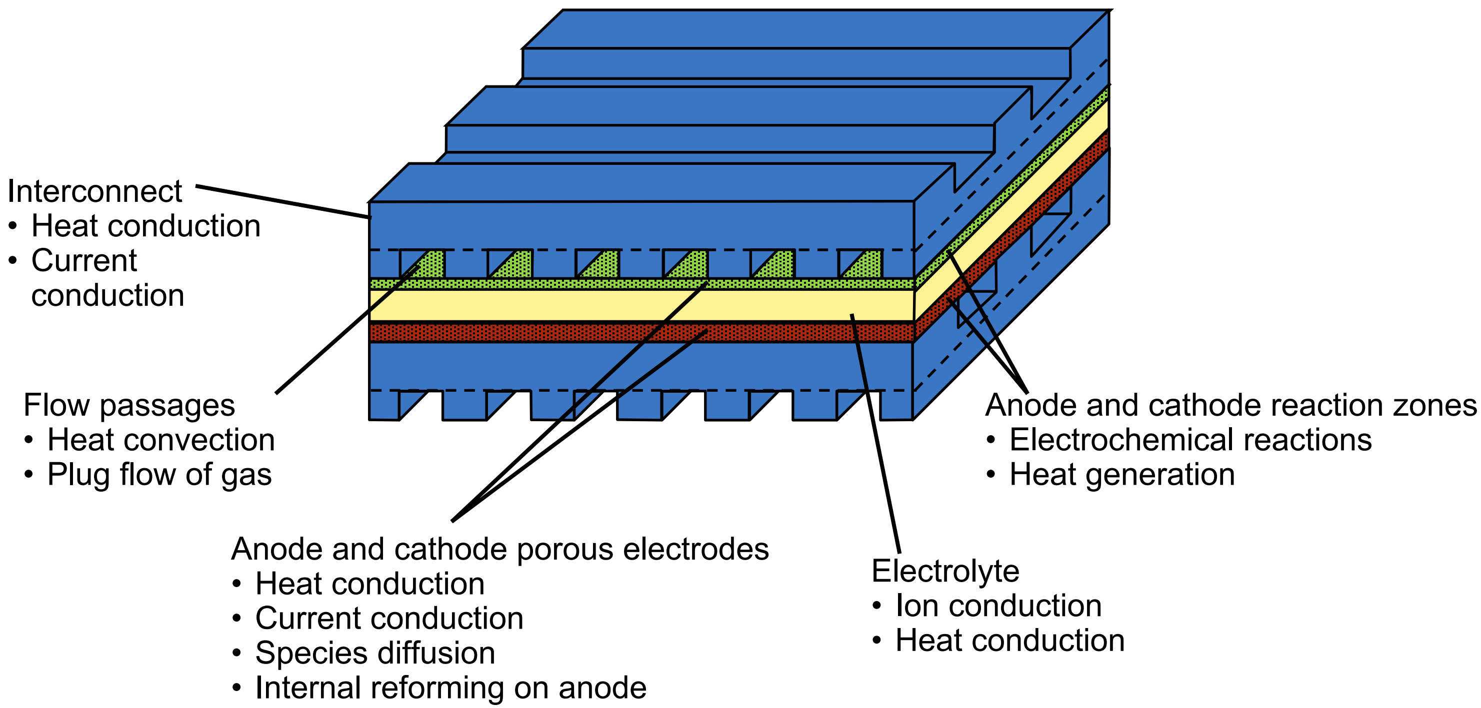
Calculation Engine (Activity-Based)
- Process flow
- Equipment options

Outputs (Results)
- Tables
- Graphs
- Crystal Ball
  - sensitivity
  - “frequency distribution”

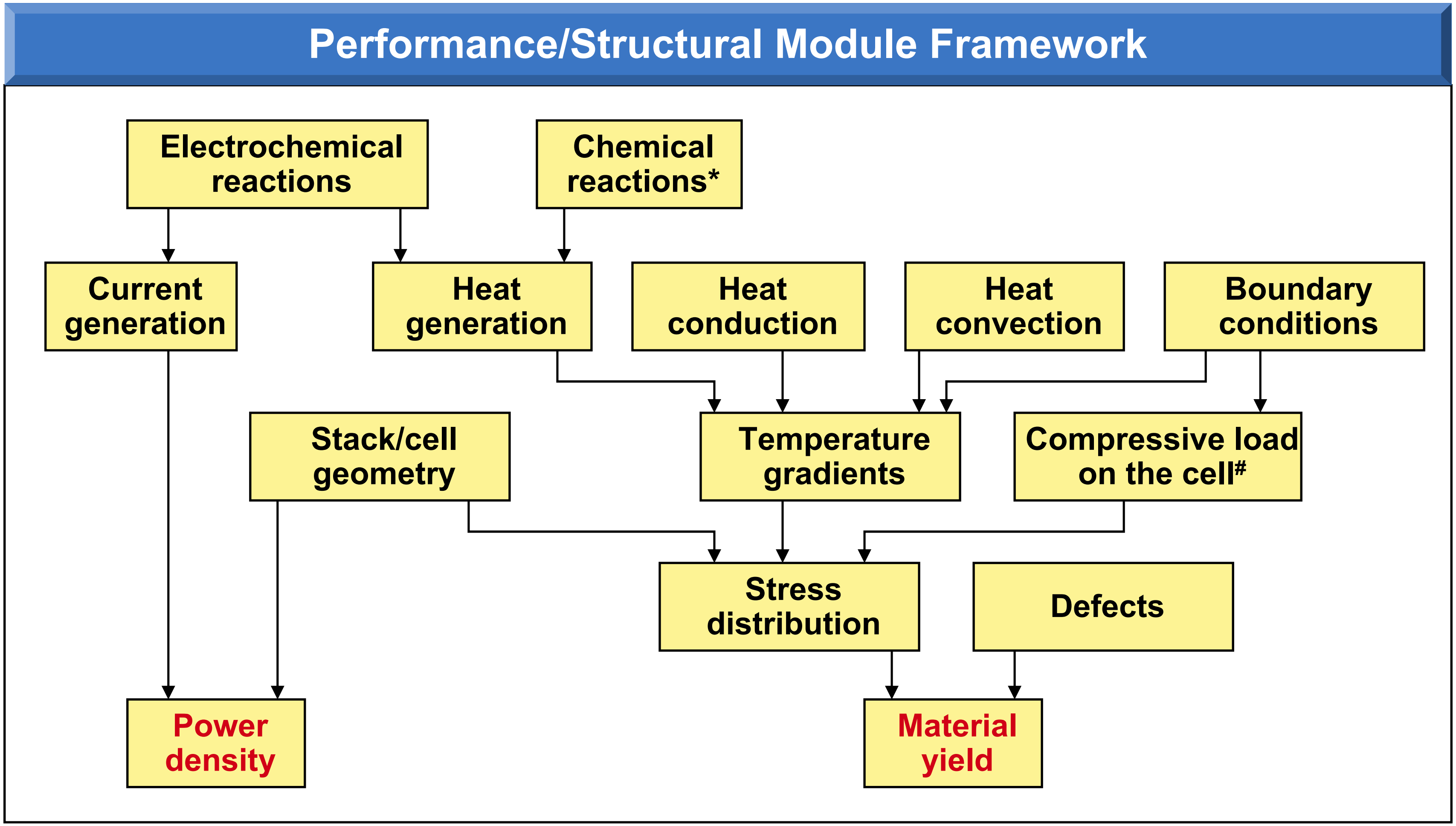
Manufacturing Costs	Material Cost Database	Material Properties Database	Purchased Components	Formulation Database	Process Database	Capital Equipment Database
• Labor • Real estate • Overhead . . .	• Vendors • Cost vs. volume . . .	• Density • Particle size distribution • Surface area . . .	• Cost vs. volume • Specifica-tions . . .	• Anode • Cathode • Electrolyte • Interconnects	• Equipment process data • Throughput • Size limit • Automation • Scrap • Yield	• Cost vs. product volume

The model description provides a unified framework for discussion of input parameters of interest to the Team members.

The module also accounts for all the relevant thermo-electrochemical phenomena which influence cell performance and, ultimately, cost.



The performance/structural module is used to predict power density, thermal stresses, and other performance factors that influence cost.



* Internal reforming reactions
\# Compressive load needed for establishing contact between different stack layers

1 Technical Issues

2 R&D Objectives and Approach

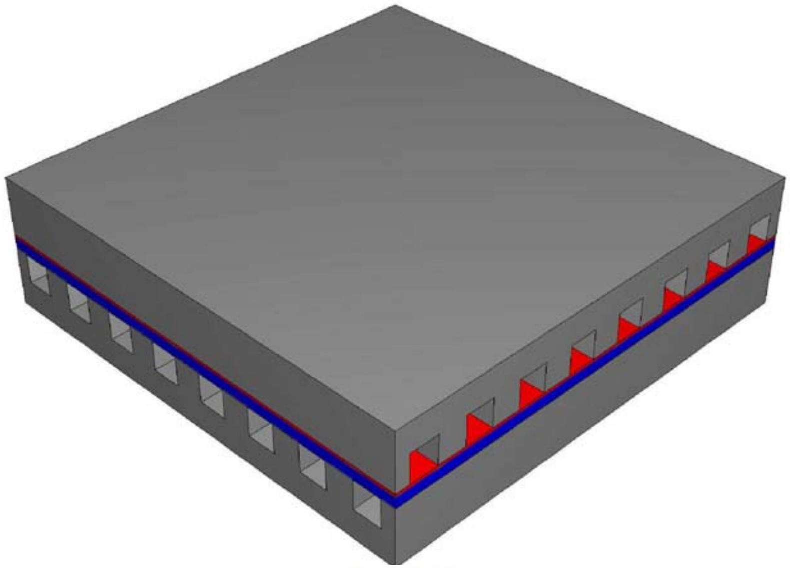
3 Activities for Phase I

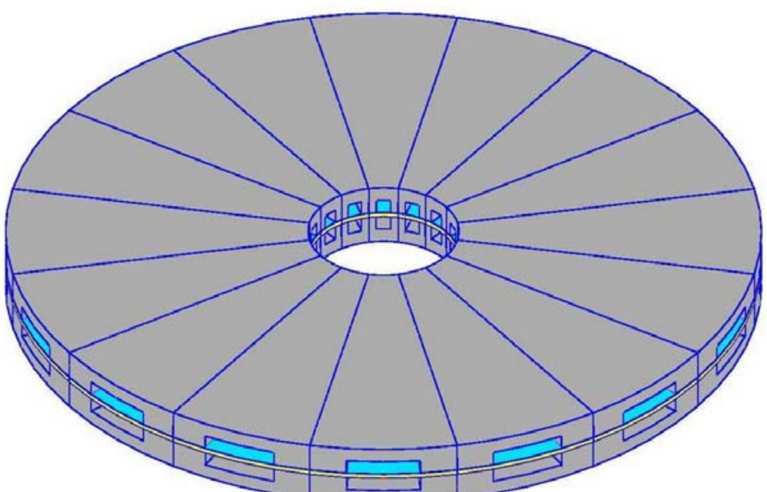
We met with the SECA technical teams to discuss what relationships among cell and stack design, design tolerances, stack performance, and process yields should be considered in Phase 1?

- Properties of individual layers
  - Thickness and other physical attributes
  - Polarization and conductivity (electrical or ionic)
  - Transport
  - Mechanical
- Manufacturing Options
  - Individual process steps
  - Sequence of steps
- Impact on
  - Process yield, tolerances, and reproducibility
  - Performance
  - Thermal cycling and life
  - Cost

We discussed selection of a stack design for demonstration of the model capabilities and an initial assessment of the impact of selected manufacturing/design factors.

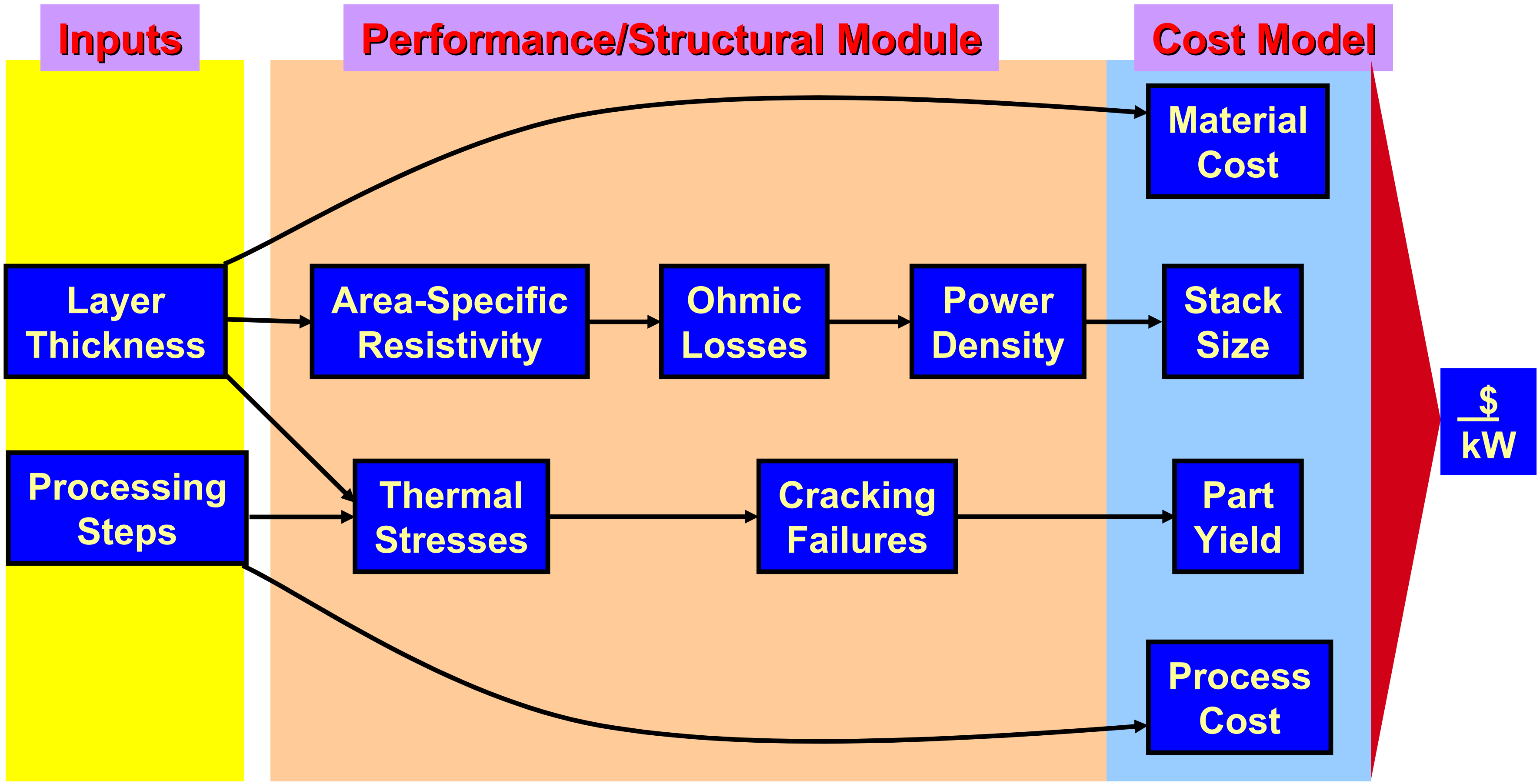
- What planar stack configuration should be modeled in Phase I?
  - Rectangular or circular
  - Co-, counter-, or cross-flow
- What design details (e.g., seals, manifolds, insulation) should be included in the Phase I modeling effort?
- What size (kW) stack should we consider?



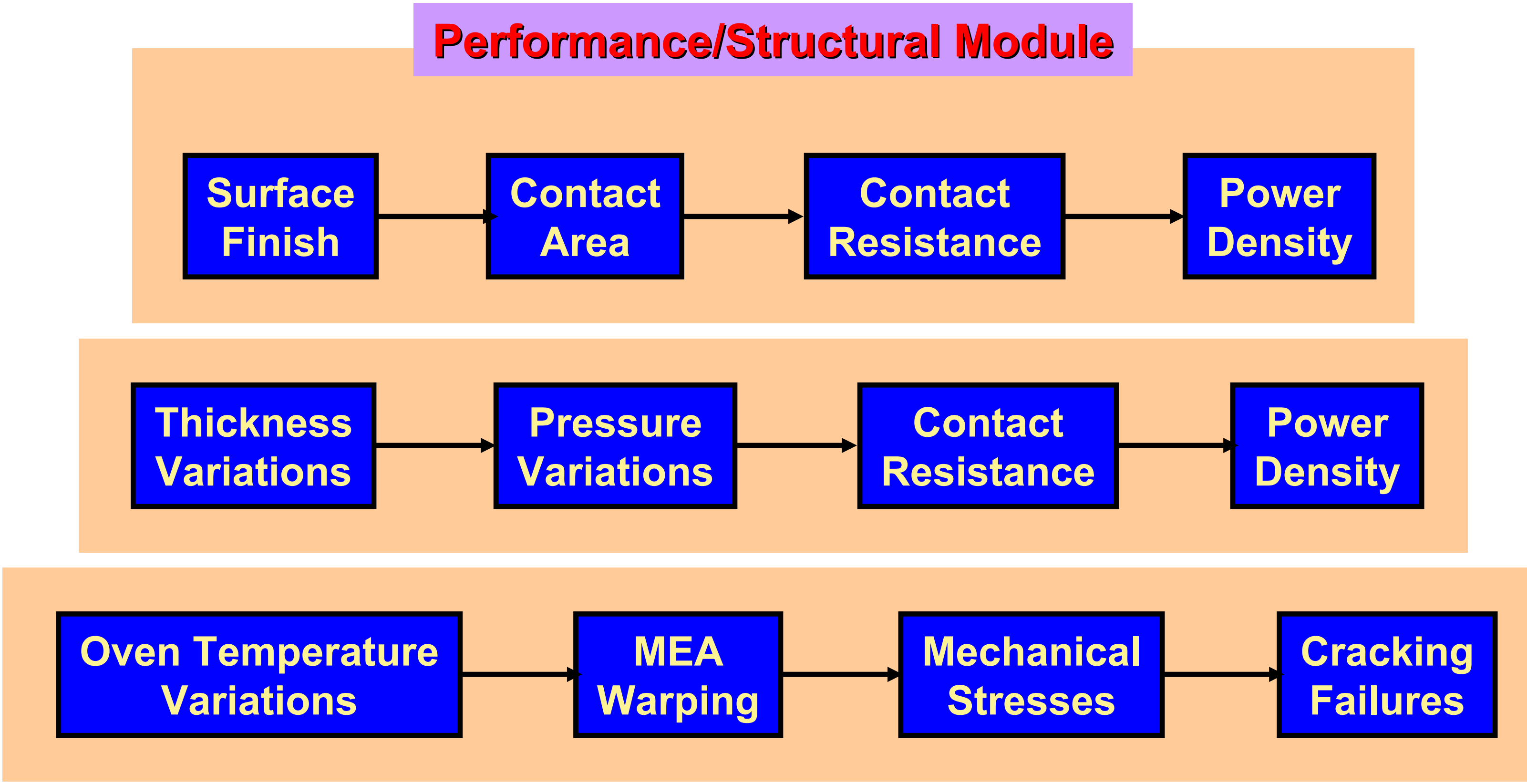


What choices affecting both cost and performance should we analyze?

- For example, we could consider the impact of layer thickness on system power and thermal stresses.



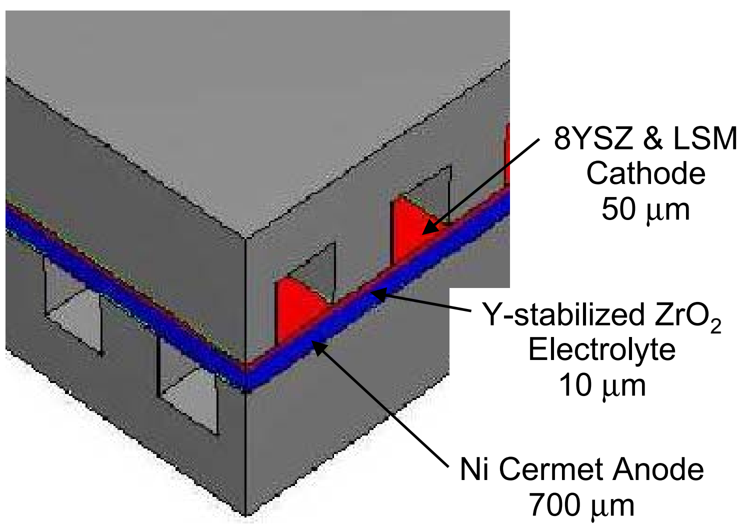
In addition, the Performance/Structural Module could be used for stand-alone simulations to evaluate the sensitivity of particular material or process parameters.



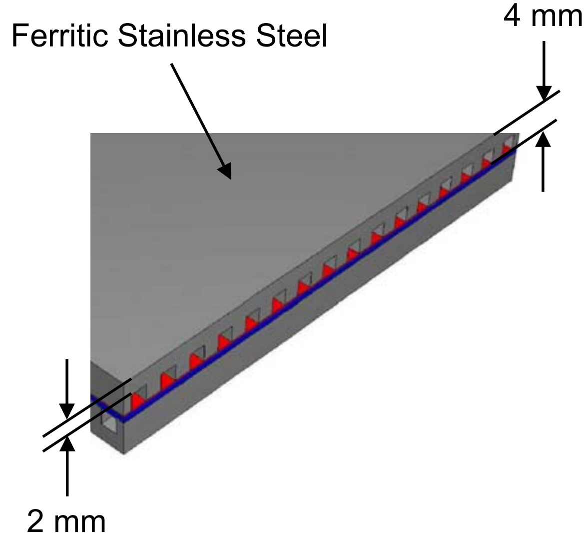
What design parameters, material properties, or manufacturing conditions are of interest for analysis, either in Phase I or II?

As a basis for Phase I, we will use an anode supported design.

Anode/Electrolyte/Cathode



One-Half Interconnect Layer



We will only assess the stack costs in this phase. We also considered inclusion of reforming layers or materials in the stack, but have insufficient design information in this Phase of work.

We propose using the following set of operating parameters for the stack.

Parameter	Value/Range
• Cell voltage	• 0.7 V
• Power Density	• 500 mW/cm^2 (not reactant limited)
• Composition of the reactant streams	• Anode: reformate; Cathode: air
• Gas inlet temperatures	• 650°C at the Anode and Cathode
• Fuel utilization	• ~ 50 %
• Cathode stoichiometry	• ~ 5, adjusted to effect an exit temperature of 800°C.

The performance model will calculate the current distribution over the electrode, the average power density, and the actual fuel utilization.

We will look at the trade-offs between layer thickness and their impact on performance and cost. The latter impacted by material quantities and yield.

Layer	Material	Nominal Thickness (μm)	Remark
Anode	Ni-YSZ	700	• Minimize thickness to reduce material weight and resistance • Impact of thickness on strength and MEA stress
Electrolyte	YSZ	10	• Barrier properties vs thickness critical • Impact of coating technology and thickness on defects
Cathode	YSZ- LSM	50	• Coating technologies
Interconnect	Metal	4300	• Roll form technique used in baseline study

As part of this effort we will look at the impact of the attributes of various process technologies on each layer, types of defects, and number of defects. It will be critical to find relationships between defects, materials, and processes.

We will consider how production volume impacts cost ($/kW).

- Assumptions
  - 5 kW unit size
  - unit operations are automated to achieve uniformity and maximize yield
  - increasing volume can change equipment scale, speed, material logistics in the process, and automation of assembly
- Parameters
  - Days per week
  - Shifts per day
- Commercialization (Volume) Steps
  - Production Prototypes
  - Market Entry
  - Market Penetration

Our 1999 study was made assuming 250 MW, however, we have not fixed the volume steps at this time for this project.

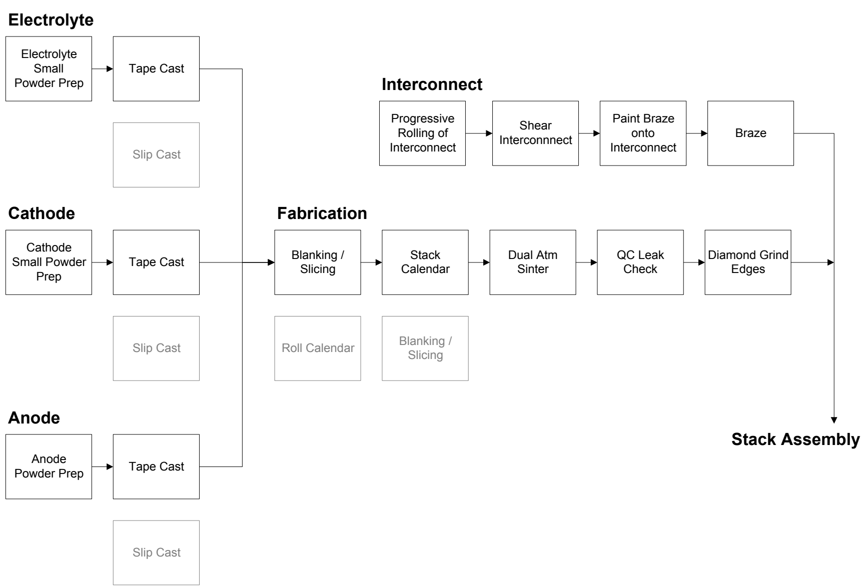
We will look at a multi-fired process flow option in Phase I.

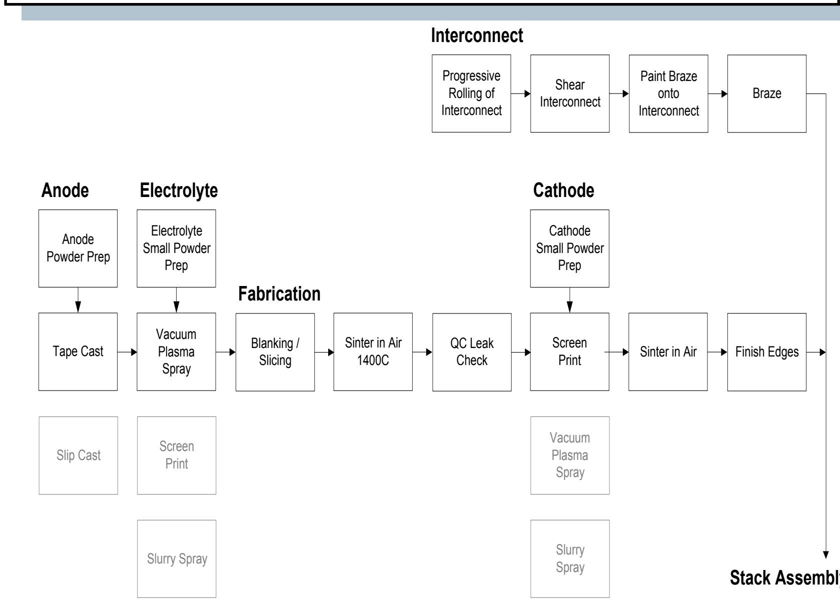
Co-fired Process Flow

- Individually tape-cast layers
- Laminated together
- Co-fired in one step

Multi-fired Process Flow

- Tape-cast anode layer
- Electrolyte and cathode layers applied by coatings
- Sequential firing steps

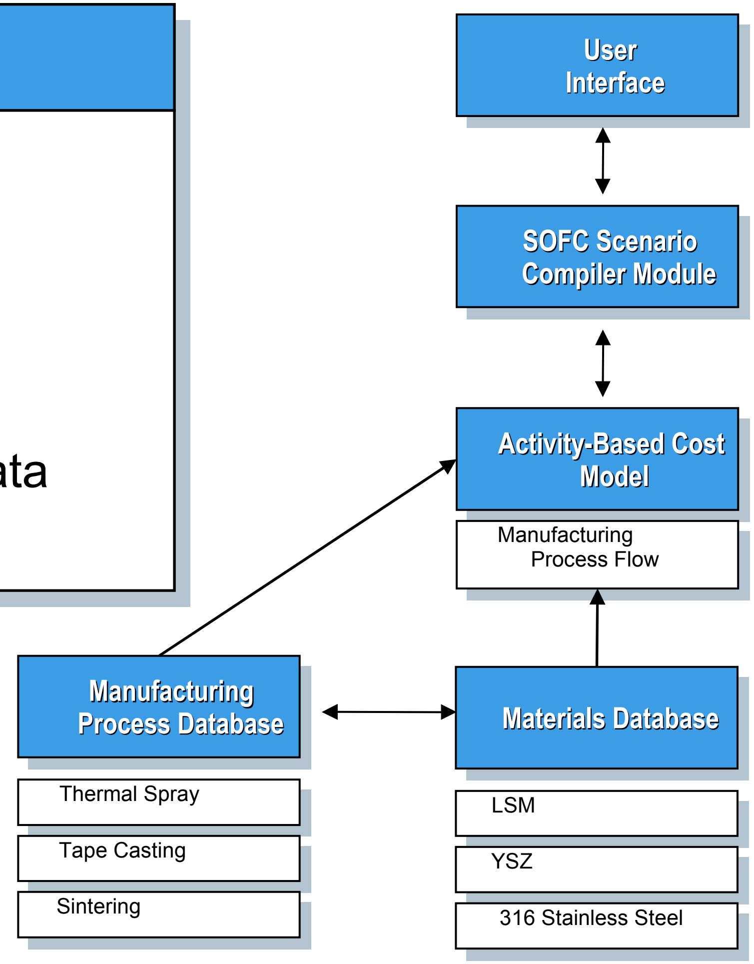




In this phase, we will use generic data, however, for Phase 2 we will have to develop a protocol(s) for protection of proprietary information with participating teams.

Issues:

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



We expect Phase I to be completed in approximately 3-6 months.

- Modify Model and Analyze Selected Scenarios and Issues
  - Layer thickness and processes
  - Economies of scale
- Discuss results with SECA teams
  - Develop plans for Phase 2
- Phase I Final Report

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

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