ceramatec®
Advanced Materials & Electrochemical Technologies

Ceramic μ-Channel Devices

μ–Processors for Macro-Processes

Funded
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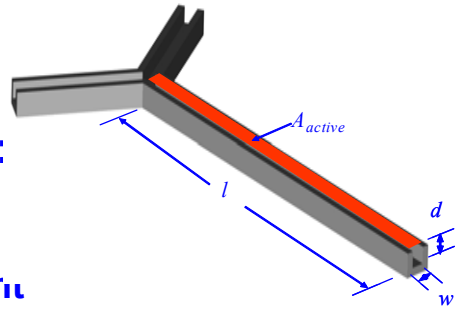
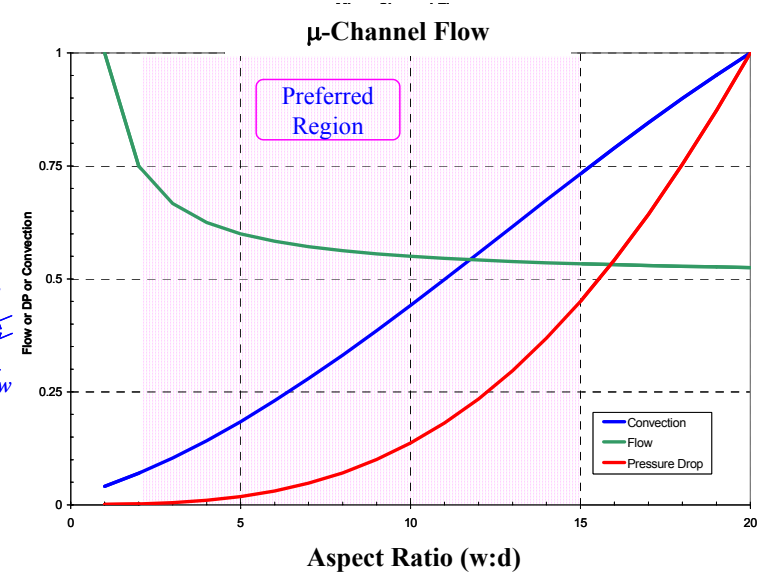
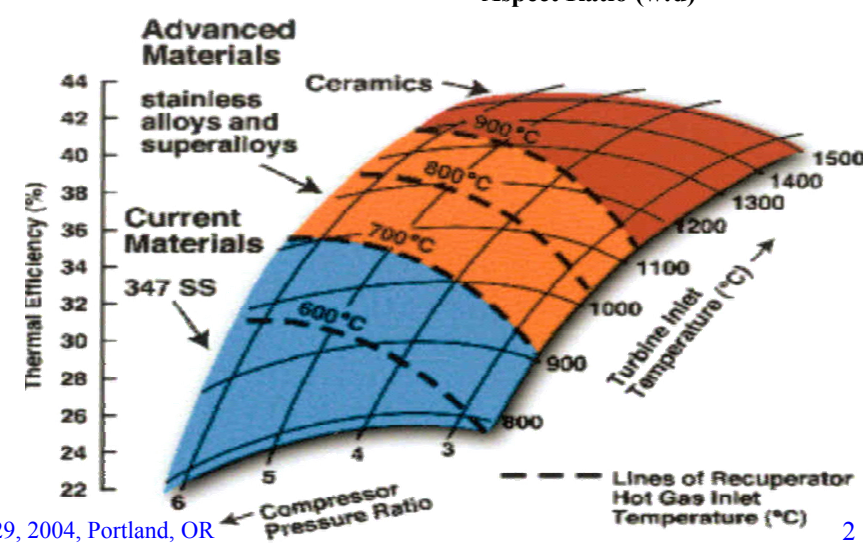
Why Ceramic μ-Channels?

- **μ-Channel Technology**
  - **Improves:**
    - **Heat Transfer**
    - **Mass Transfer**
  - **Therefore Reduces:**
    - **Reactor Volume**
    - **Residence Time**
    - **Capital Investment**



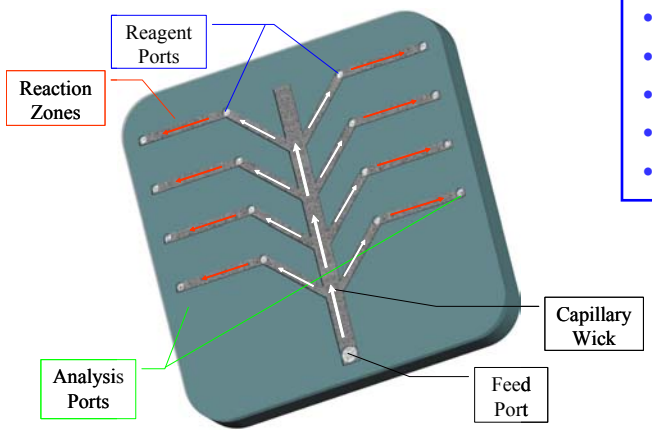


- **Ceramic Materials**
  - **Improve:**
    - **Temperature Stability**
    - **Chemical Stability**
    - **Mechanical Properties**
  - **Therefore Increase:**
    - **Operational Life**
    - **Materials Compatibility**
    - **Process Temperatures**



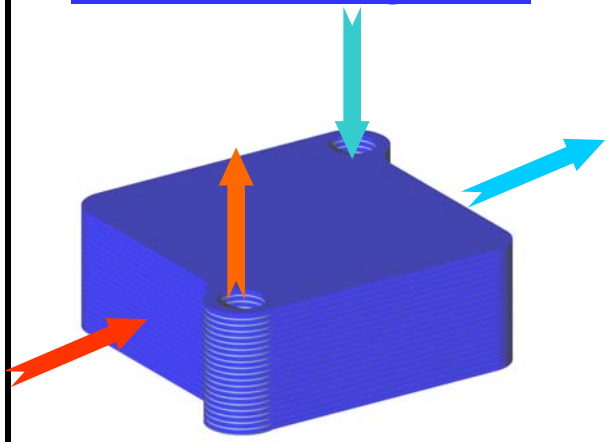
What Applications?

Analytical



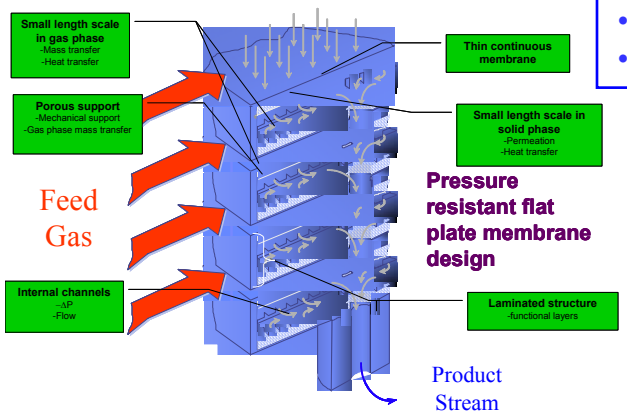
- "Lab-on-a-chip"
- Wet Chemistry
- Gas Titration
- Catalysis
- Thermal Effects

Thermal Management



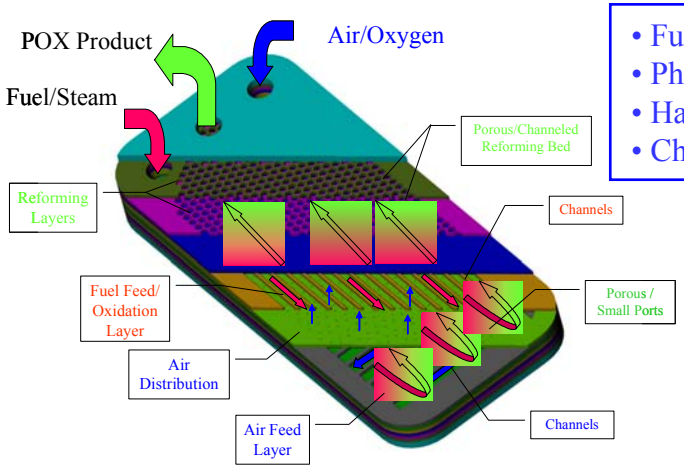
- Electronics Cooling
- Heat Pipes
- Evaporator
- Condenser
- Hot Gas to Gas
- Corrosive Mediums

Separations



- Selective Membranes
- Porous Membranes
- Multi-Phase

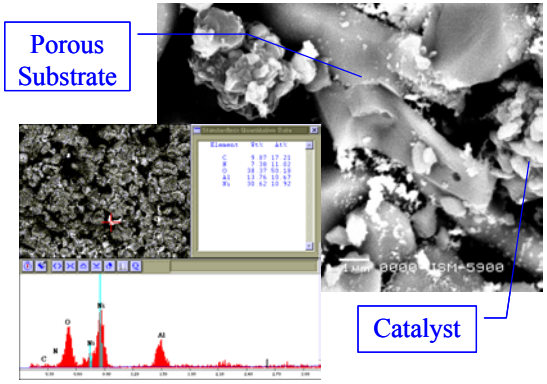
Combined / Reactors



- Fuel Processors
- Pharmaceuticals
- Hazardous Mat'ls
- Chemical Synthesis

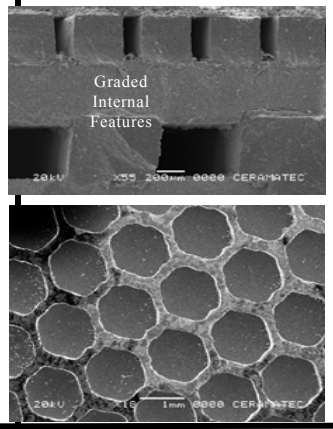
Processing Skill-Base

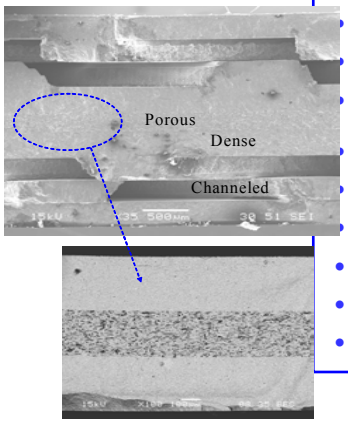
Catalyst Impregnation



- High Surface Area
- Selective Catalyst
- Graded Porosity

Graded Structures

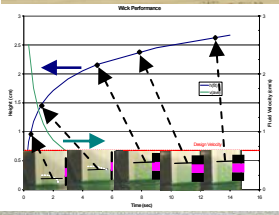




- Dense Membranes
- Porous Membranes
- Micro-Channels
- Mini-Channels
- Flow Distribution
- Heat Transfer
- Mixing
- Separations
- Filtering
- Reactions

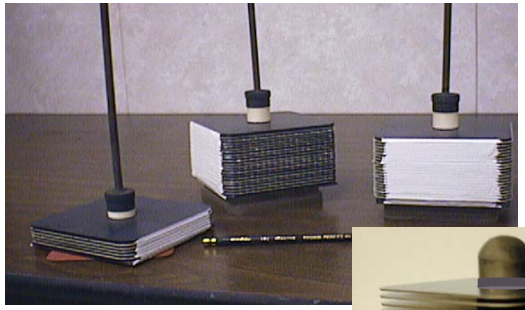
Micro-Channel Devices

- Chemical Reactors
- Heat Exchangers
- Separation Membranes
- Capillary Wicks
- Fluid Mixers



- Internal Manifolds
- External Interfaces
- Primary Unit Cell

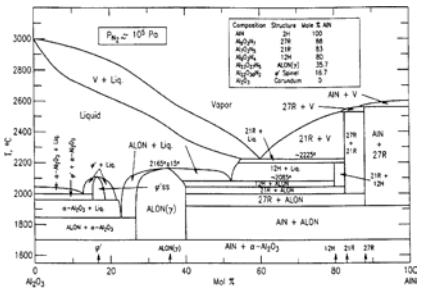
System Fabrication

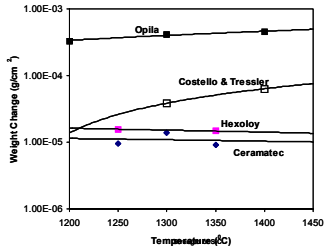


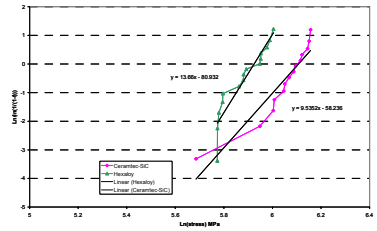
- Process Scale-up
- External Plumbing
- Mechanical Integrity
- Multi-Step Processes

Engineering Skill-Base:

Materials

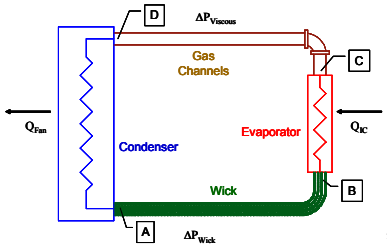


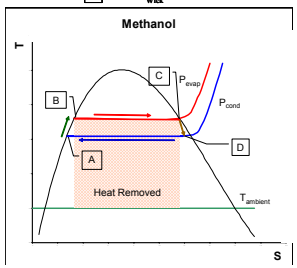


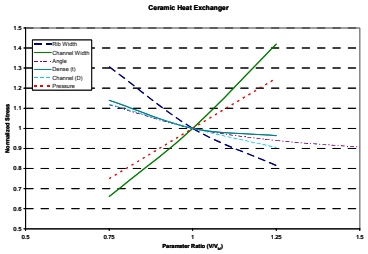


Testing

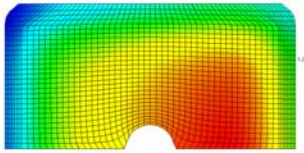
Design

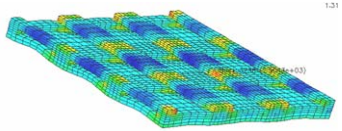


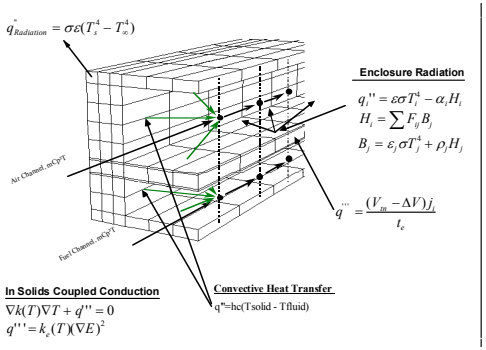




Analysis







Rapid Prototyping Complex Devices:

•Flexible Microchannel Designs and Processes.

Fabrication Method

Tape Cast
(Solvent Based)

↓

Features/Slots
(Laser Cut)

↓

Lamination
(Heat/Pressure/Solvent)

↓

Sinter

Multi-Faceted Development

Module, Component & Channel Design
Operational Performance

Thermal / Fluids
-System Integration
-Heat Exchange
-Flow Dynamics
-Effectiveness

Mechanics
-Localized Stresses (features)
-Thermo-mechanical Loads
-Global / Coupled Stresses

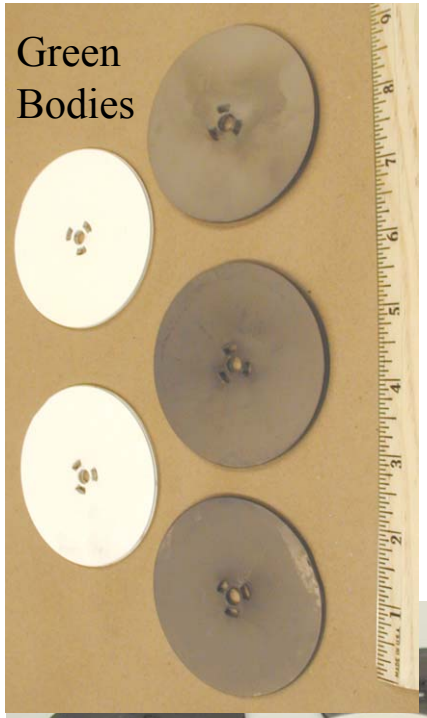
Ceramic Processing
-Machining Capability
-Assembly Tolerances
-Sintering (Densification)

Layer & Channel Dimensions
Reaction Chemistry

Materials
-Thermal Properties
-Corrosion
-Strength
-Creep

Materials Processing
Operational Life

Fabrication of μ-Channel Components



Dense – Heat Transfer Surface

/ Slotted – Combustion Channels

\ Slotted – Combustion Channels

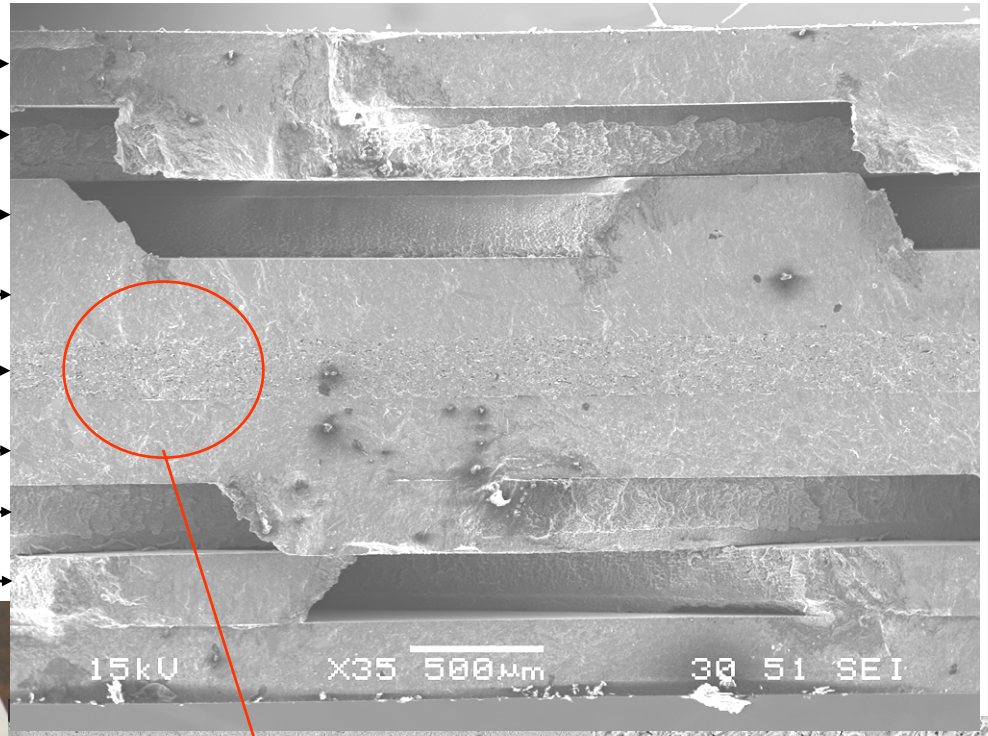
Porous Mask – Flow Restrictor

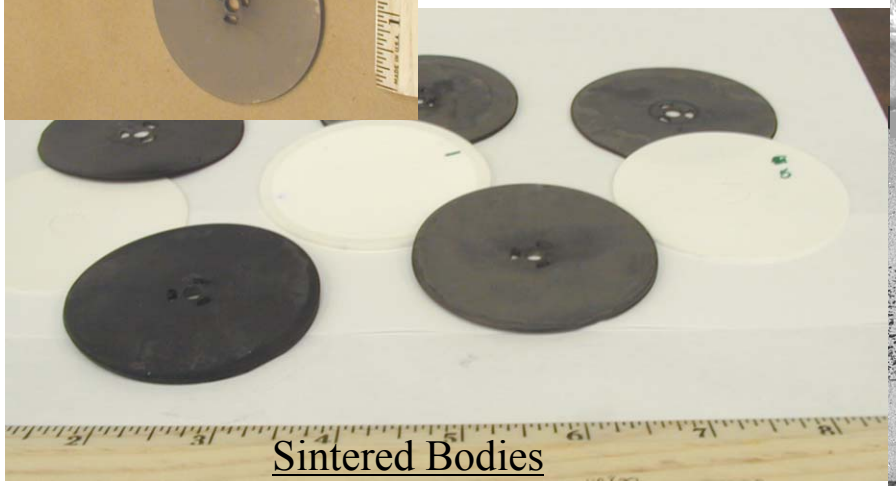
Porous – Flow Regulator

Porous Mask – Flow Restrictor

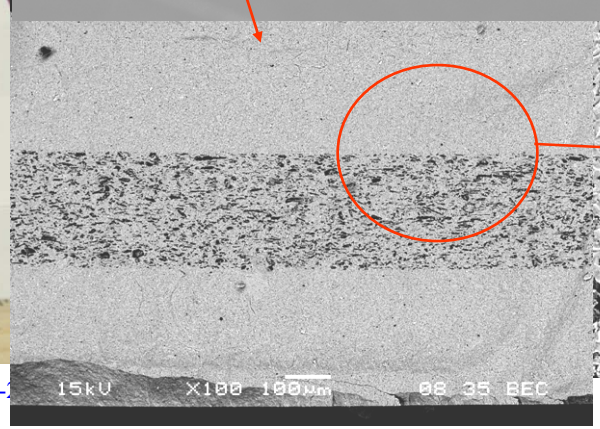
/ Slotted – Fuel Distribution

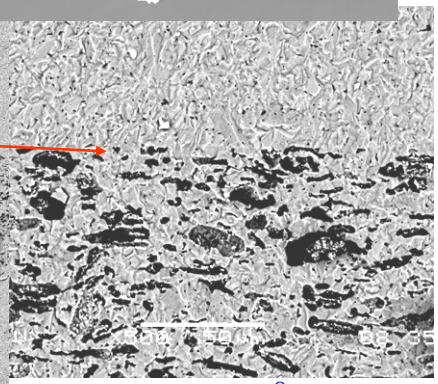
\ Slotted – Fuel Distribution





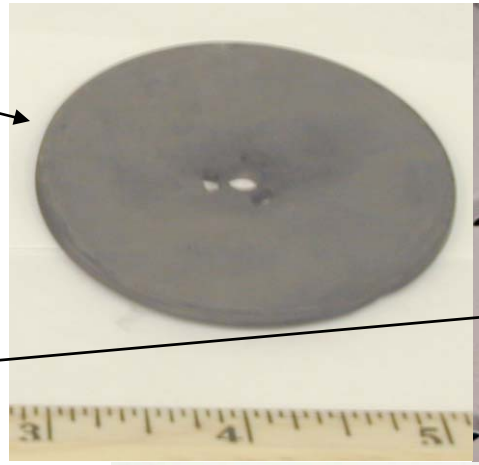
Sintered Bodies

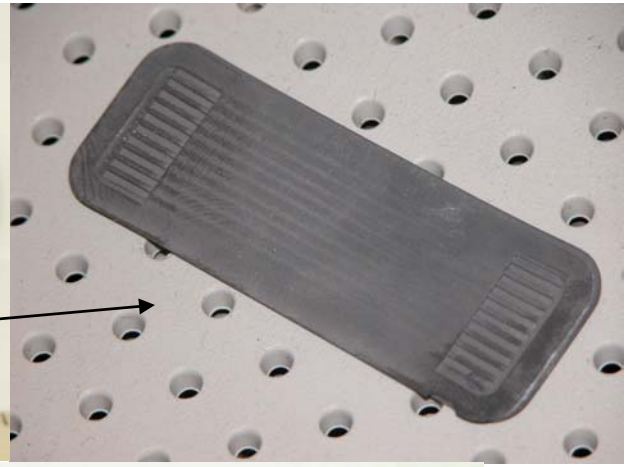




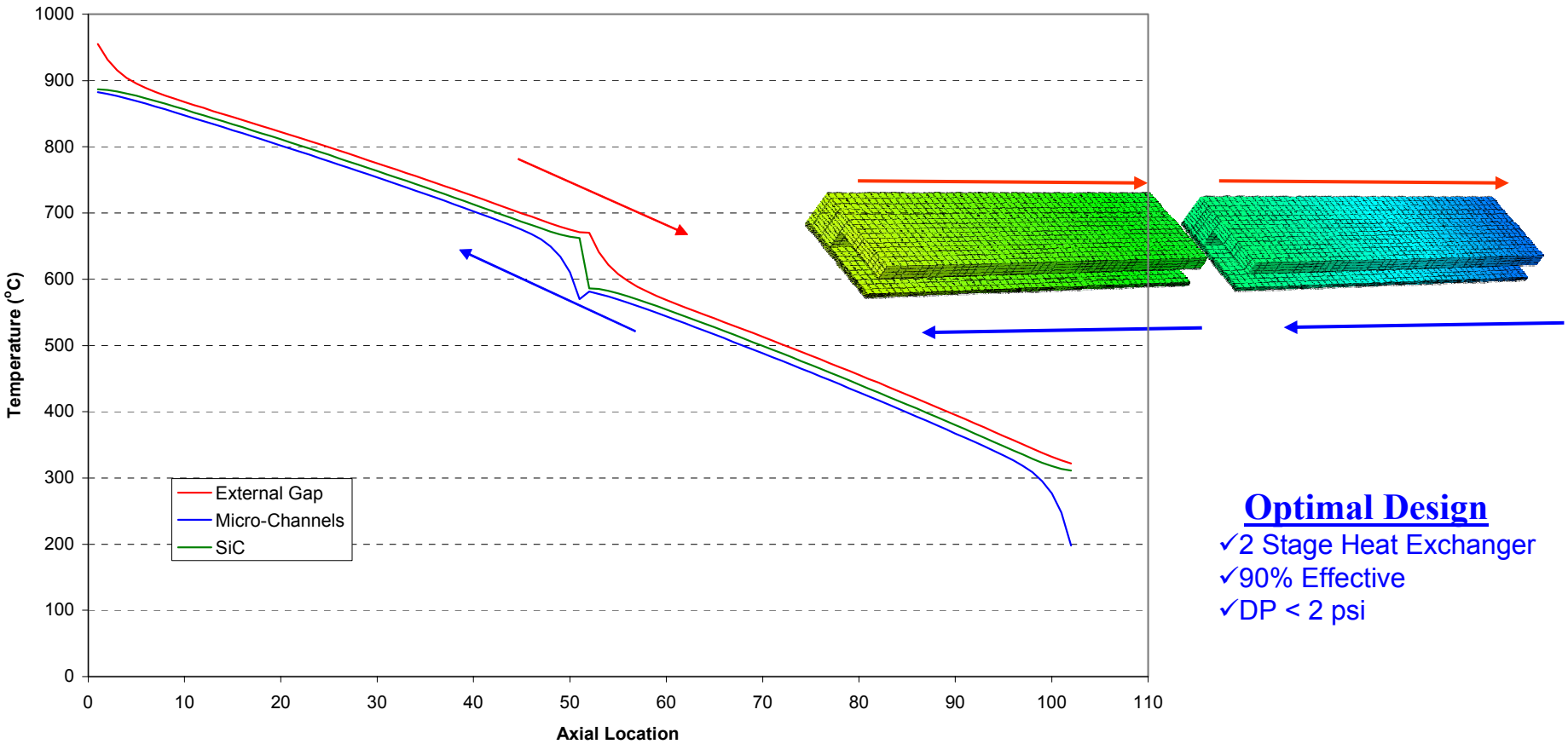
Fabrication Development – Scale-up

- **Phase 1 Wafers**
  - **Radial Flow**
  - **2 Fluid (Air/Methane)**
  - **14 Layer Structure**
- **Test Coupons**
  - **Flow Testing**
  - **Heat Transfer Testing**
  - **Counter-Flow**
  - **Channel w:d parametrics**
- **Full-Size Wafers**
  - **Commercial Scale**
  - **108mm x 108mm x 1.5mm**
  - **Channels: 72 channels/wafer**
    - **100mm*1900μ*200μ (l*w*d)**
    - **w:d = 9.5**
  - **Leak Tight**





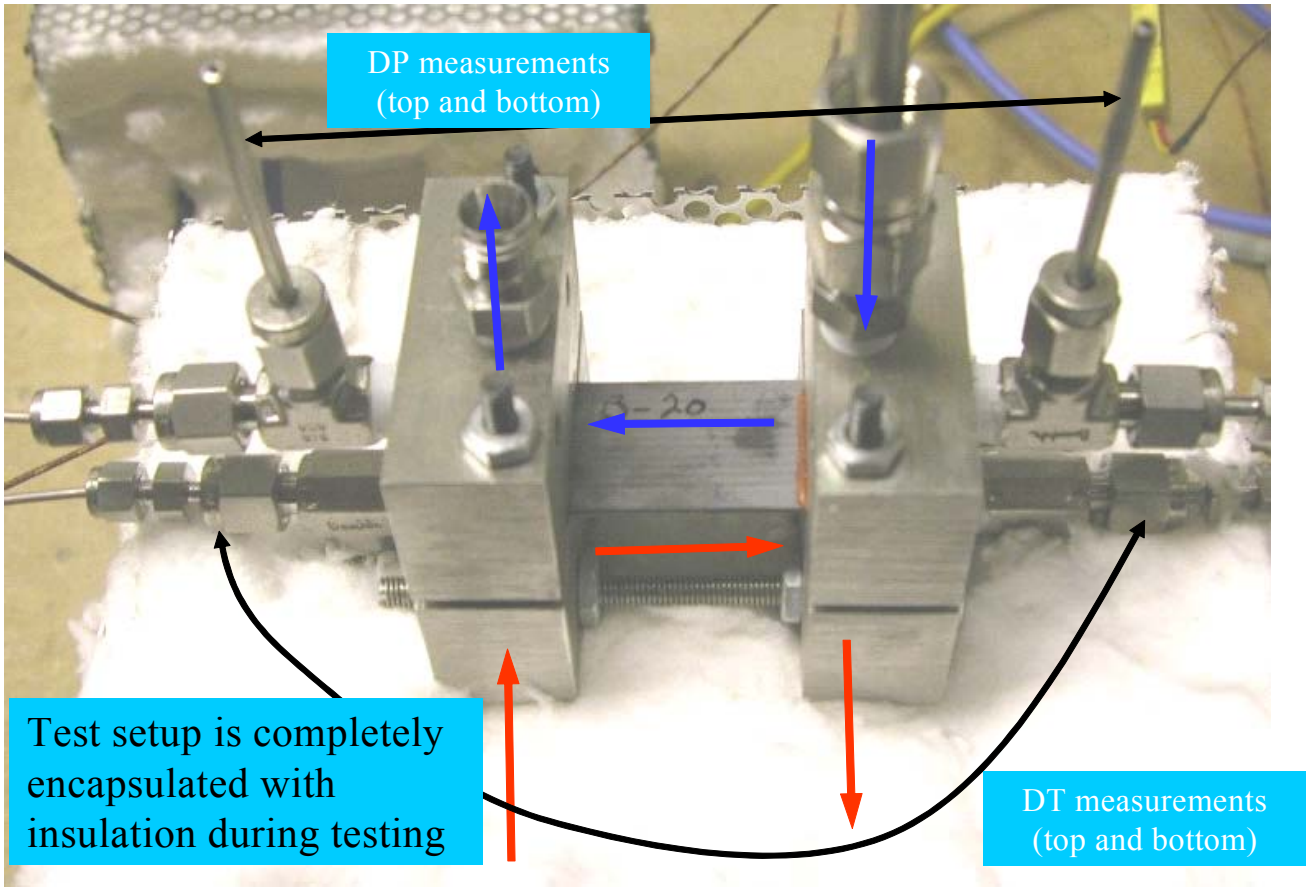
Layer & Feature Optimization



Optimal Design

- ✓2 Stage Heat Exchanger
- ✓90% Effective
- ✓DP < 2 psi

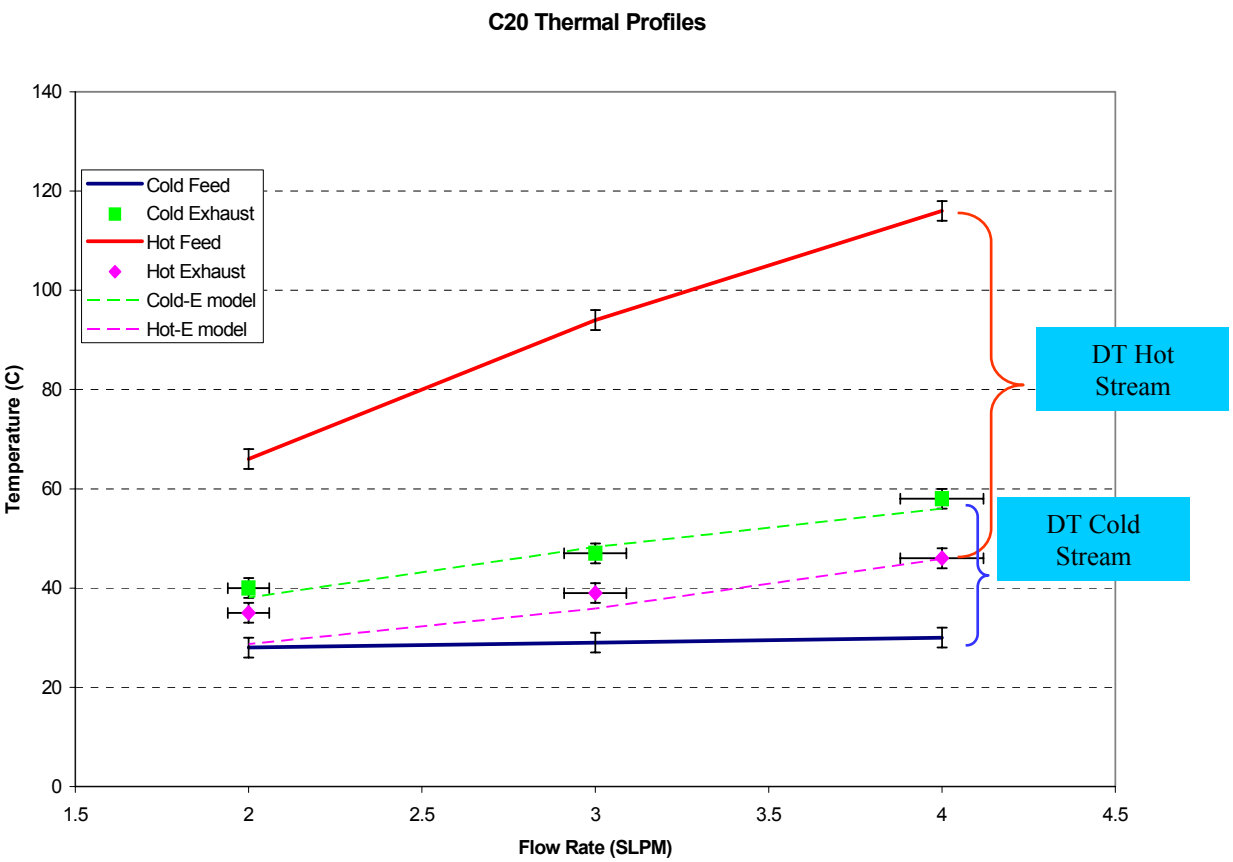
μ-Channel Validation Testing

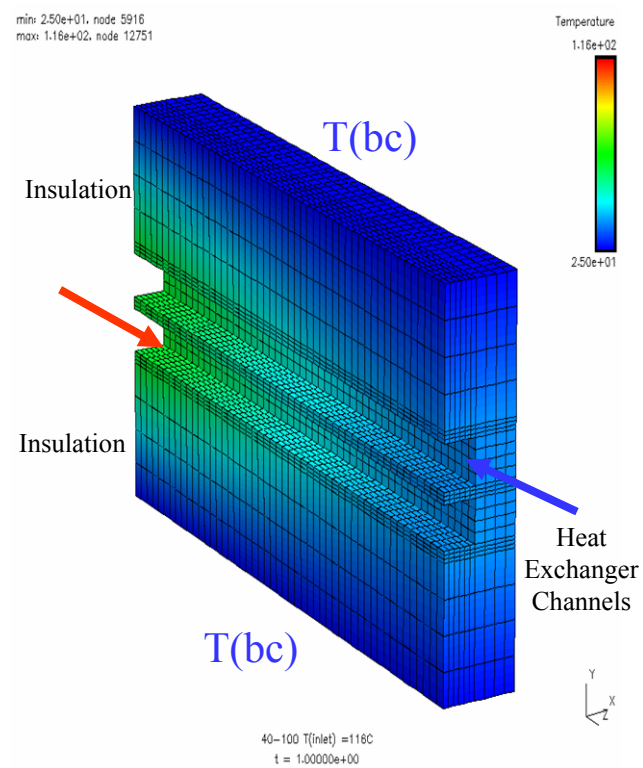


- **SiC Ceramic**
  - **Counterflow**
  - **Internal Channels**
- **Test Variables**
  - **Channel (w,d, w:d)**
    - **500μ < w < 2000μ**
    - **250μ < d < 500μ**
  - **Flow Rates**
    - **1 LPM < Q < 4 LPM**

μ-Channel Testing: Heat Transfer & Models

Data vs Model

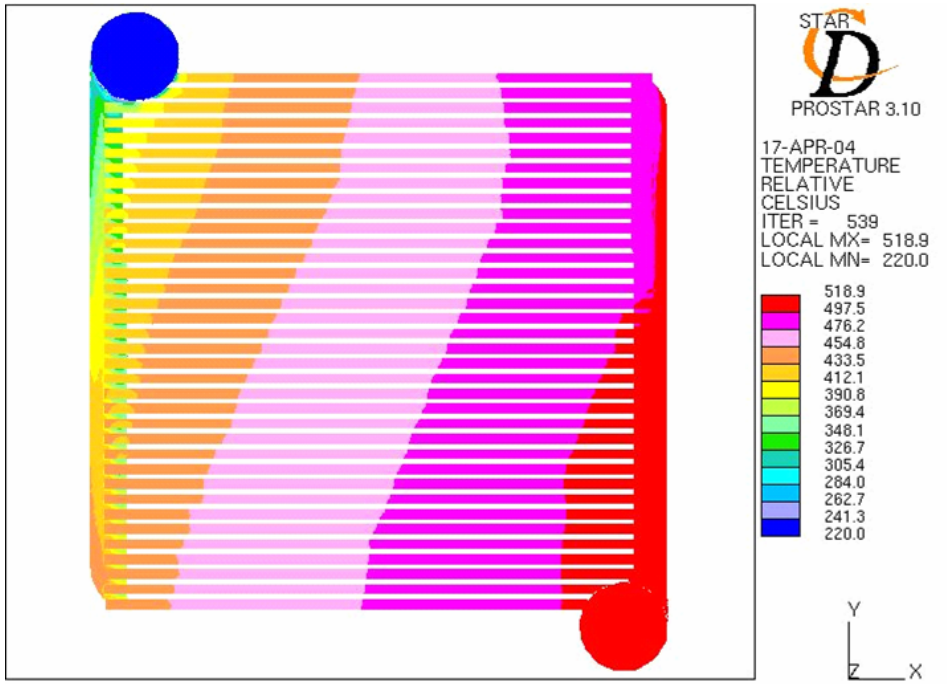


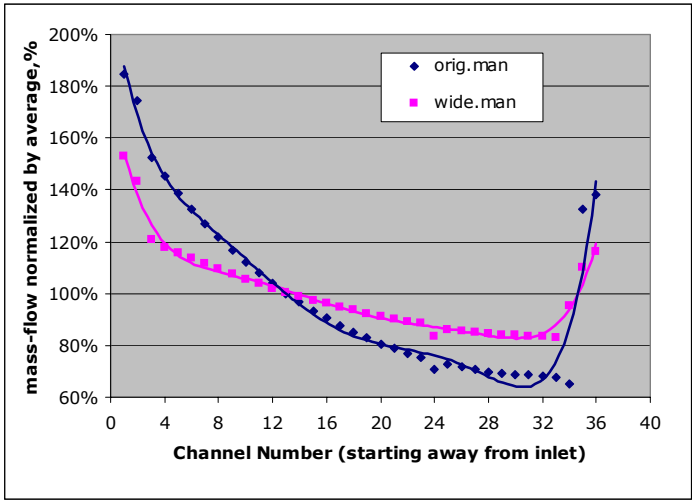


Finite Element Analysis

Wafer Scale-Up: Conjugate Flow & Heat

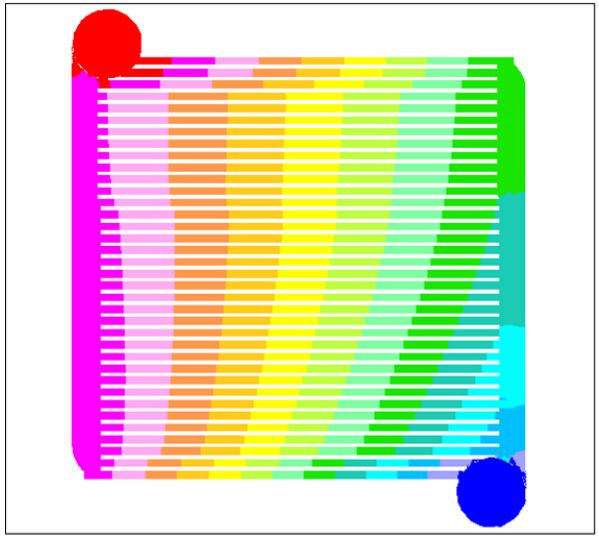
Thermal Profile





Flow Distribution

Pressure Profile



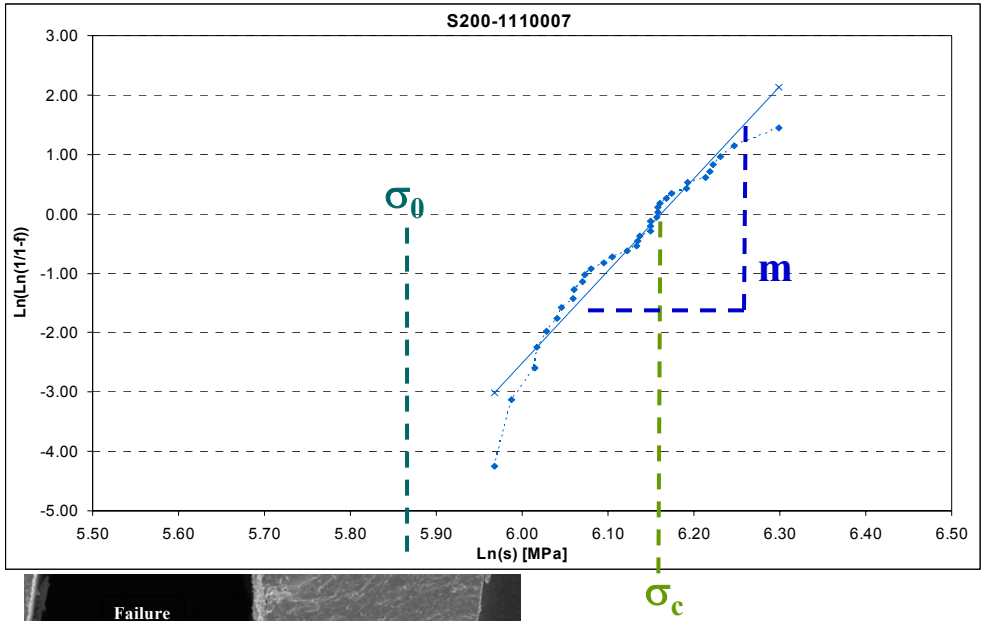
Courtesy of PNNL

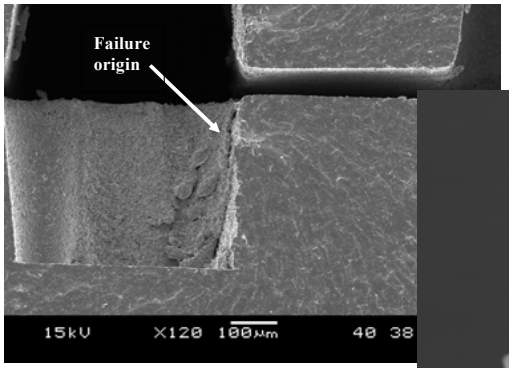
Mechanical Design: Brittle Ceramics

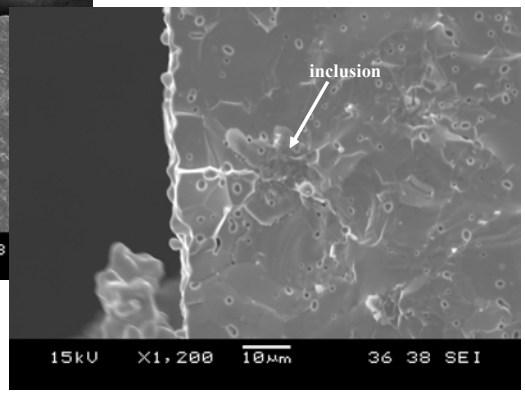
- **Failure in Ceramics is Predicted Using Weibull Distribution**
  - **2 Parameter**
    - **Characteristic Strength (σ_c)**
    - **Weibull Modulus (m)**
  - **3 Parameter (σ_0)**

- **Characterization of Flaws**
  - **Size**
  - **Location: surface, volume**

- **Reliability Data Should be Based on Similar Processes**

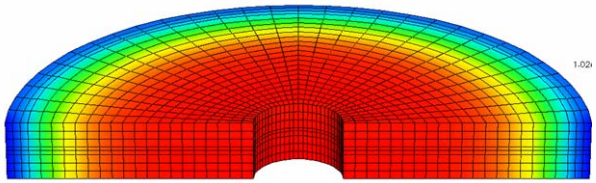




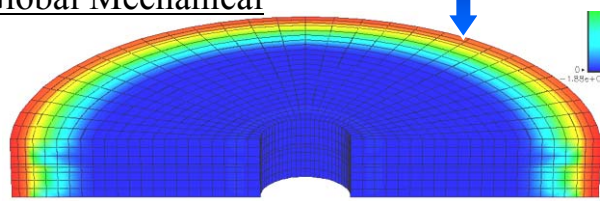


Mechanical Design: Loads & Stress

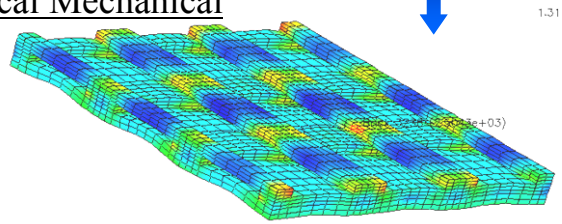
Global Thermal



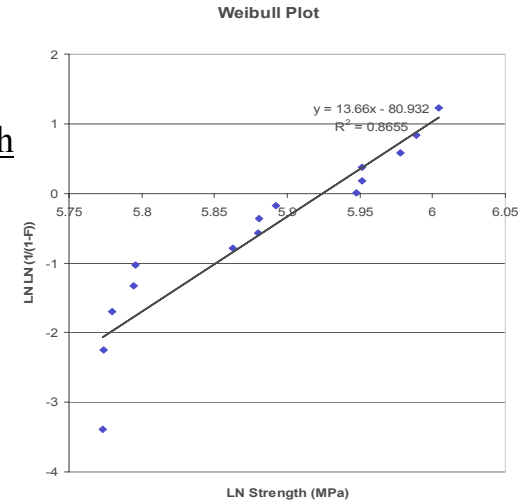
Global Mechanical

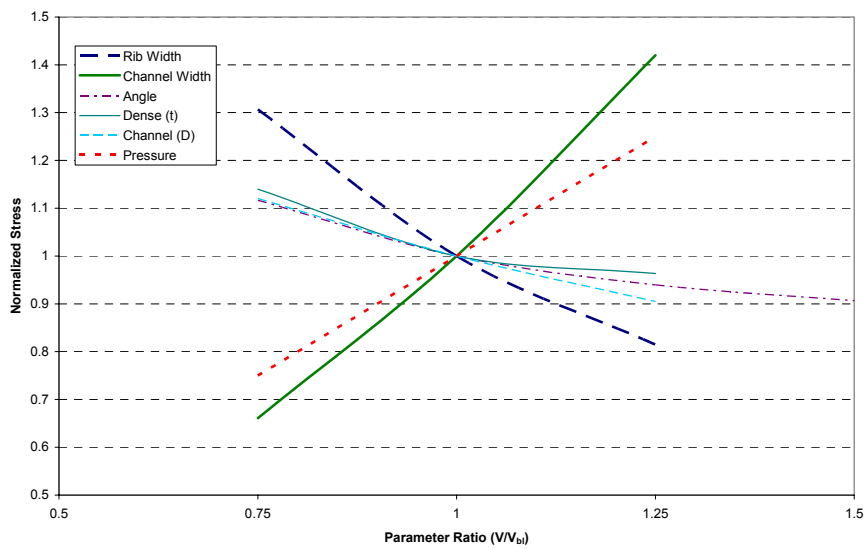


Local Mechanical



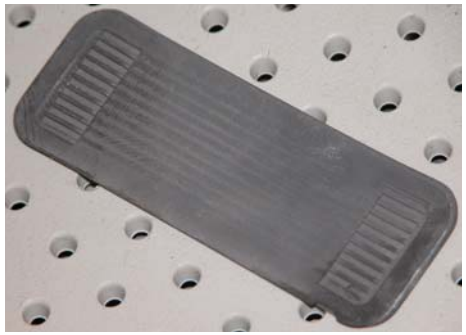
Mechanical Strength





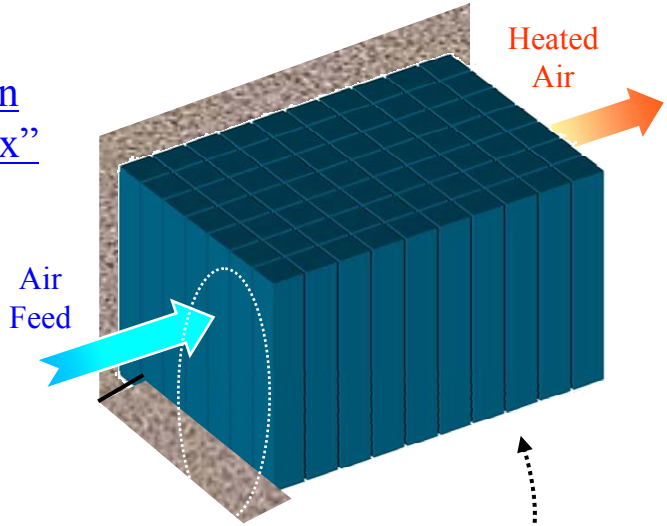
Design Sensitivity

μ-Processors for Macro Processes



Laminated "Test Coupon"

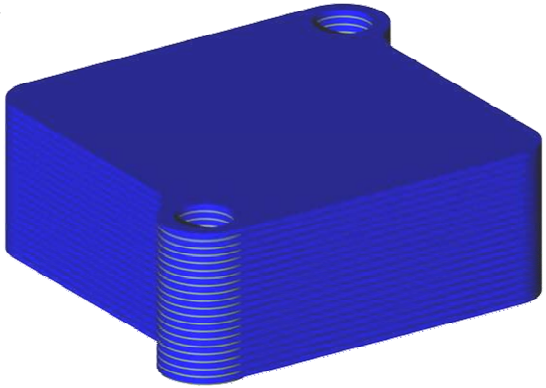
Array in "Hot Box"



Full-Size Wafer

Scale-up

Numbering-up

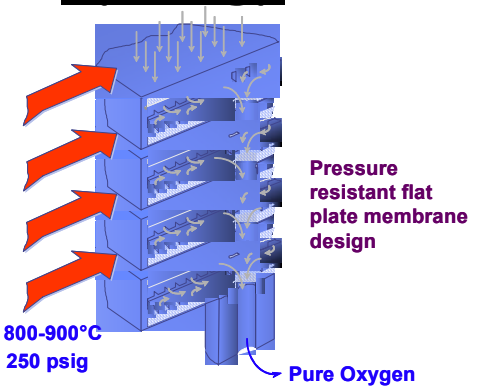


Modular Stack

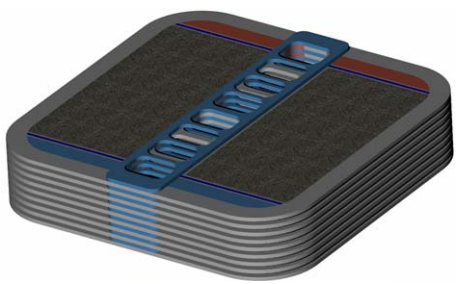
Ceramatec: Synergy, Technology, Delivery

Synergy

ITM Oxygen



ITM Syngas



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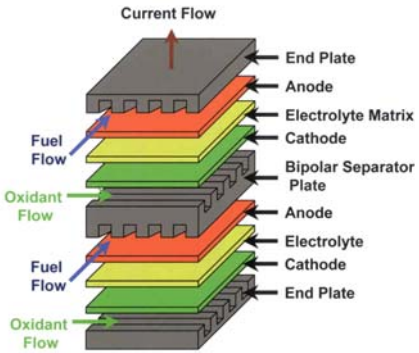


Technology

Materials

Oxide Systems

- Alumina
- Zirconia
- Ceria
- Alumina/zirconia
- Mullite
- Nasicon
- Perovskites

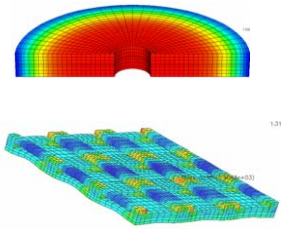
Non-Oxide Systems

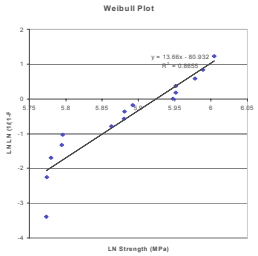
- Silicon carbide
- Aluminum nitride
- Silicon nitride
- Titanium diboride
- Silicon nitride
- Tungsten carbide

Processing

Dry Powder Processing
Powder Pressing
Tape Casting
Laser Machining
Lamination
Sintering – Air, Atmosphere
Joining
Finish Machining

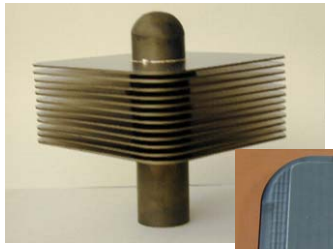
Engineering

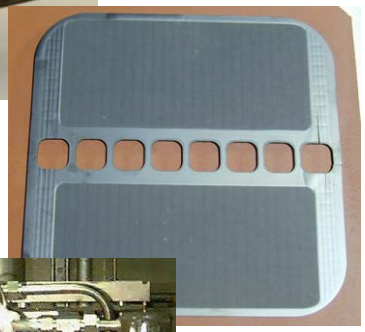


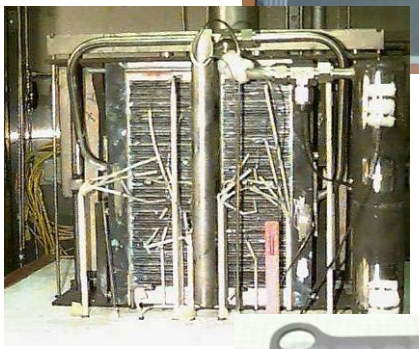


Delivery

μ-Channel Programs







Figures of Merit

Performance

- **Pressure Drop (ΔP)**
  - Internal : 4.14 kPa/Stage
  - External : 0.35 kPa/Stage
- **Thermal Differential**
  - ΔT_{ave} = 30C
- **Heat transfer Coefficient**
  - U_{ave} = 445 W/m^{2}C
- **Thermal Duty**
  - 107.5 kW

Geometric

- **Volume**
  - 0.55 m^3 (1.9 ft^3)
- **Hydraulic Diameter**
  - Internal: 325μ
  - External: 760μ
- **1470 "Wafers"**
- **2 Stages**
- **# Modules: 5x2 = 10**