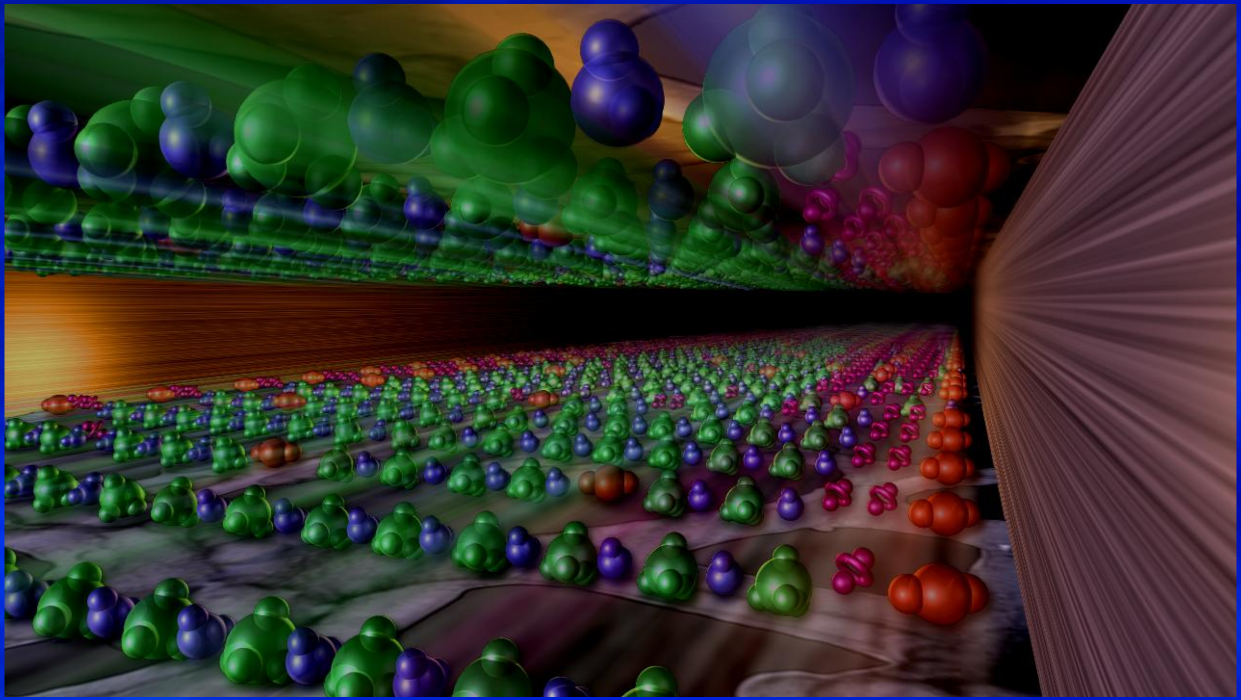


Microreaction Engineering: Is small really better?

Jan J. Lerou

Velocys, Inc., Plain City OH

www.velocys.com

Overview

Background

Fundamentals

Reaction Applications

Scale-up Methodology

Summary

Background

History

- In public domain since 1995

Definition of microstructured reactors

- 3-dimensional structures from sub-mm to mm range
- Main characteristic:

  specific surface 10,000 – 50,000 m^2/m^3

Potential benefits

- Process intensification
- Inherent process safety
- Broader reaction conditions incl. explosion regimes
- Distributed production
- Faster development

Background (cont.)

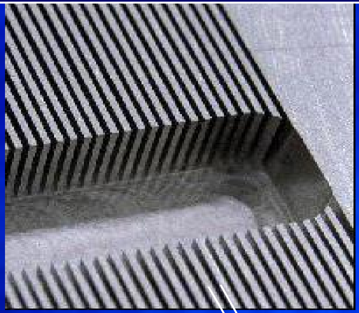
Companies currently moving microchannel technology from R&D to commercialization:

- Degussa: running a demonstration project for the evaluation of microreaction technology or DEMiSTM for propylene epoxidation with hydrogen peroxide
- Clariant: opened its Competence Centre for Microreactor Technology (C3MRT) to increase efficiency, improve safety and reduce the costs of pharmaceutical synthesis
  - Continuous pilot plan for the synthesis of azo-pigments
- Axiva developed a process for continuous polymerization of acrylates (8 kg/h) using micro mixers
- Velocys…

Enabling Technology

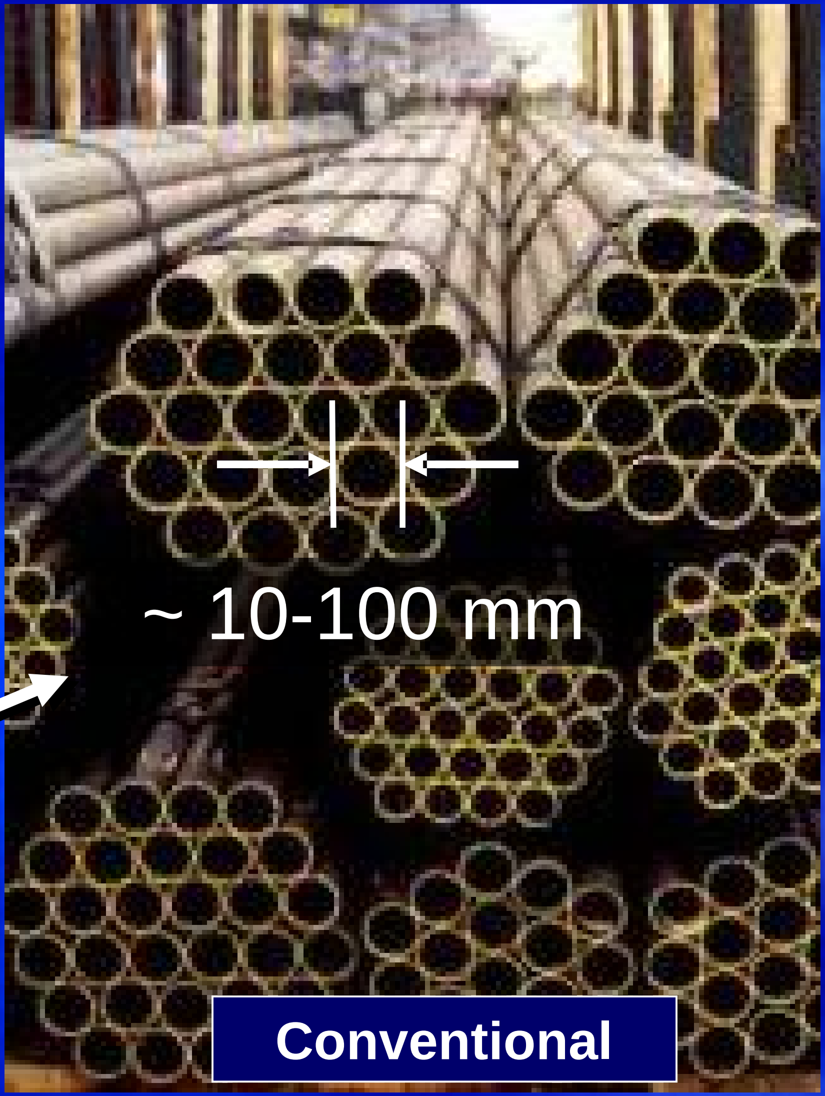
Microchannels enable compact unit operations with high capacity per unit volume by reducing transport distances

Microchannel



~ 0.1-1 mm

Characteristic dimension



Conventional Reactors

- Steam Methane Reformer
- 20 million standard cubic feet/day
- ~30m x ~30m x ~30m

Velocys® Technology Reactors

- Microchannel Steam Methane Reformer
- Same capacity
- 90% volume reduction
- ~25% reduction in overall plant costs

Microchannel Hardware Performance

Intense Heat Transfer Increases Productivity

	Microchannel	Conventional
Convective	1-20 W/cm^2	< 1 W/cm^2
Boiling	1-250 W/cm^2	< 1 W/cm^2

Fast Reactions Shrink Hardware Volume

	Microchannel	Conventional
Gas-phase	1-100 ms	1-10 seconds

Heat Transfer in Microchannels

$$h = \frac{Nu \times k}{d}$$

Nu: Nusselt number
h: Heat transfer coefficient
d: Hydraulic diameter
k: Thermal conductivity

Velocys Heat Exchanger

High surface area/volume ratio

High heat transfer per volume

Conventional Heat Exchanger

Low surface area/volume ratio

Low heat transfer per volume

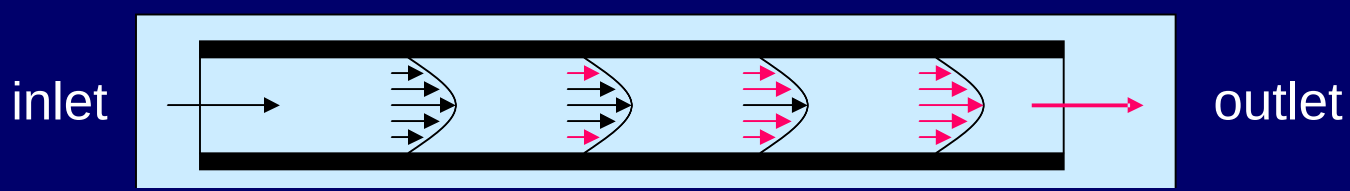
Mass Transfer in Microchannels

$$\tau_{diff} = \frac{(d/2)^2}{D}$$

τ: Characteristic diffusion time
d: Hydraulic diameter
D: Diffusivity

$$\tau_{convection} = \frac{L}{vel_{avg}}$$

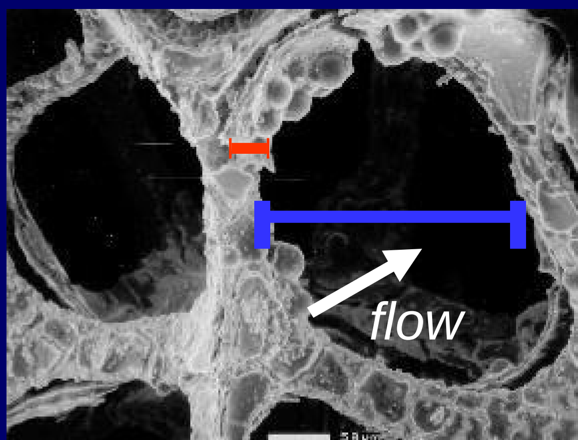
τ: Characteristic convection time
L: Flow length
vel: average laminar velocity



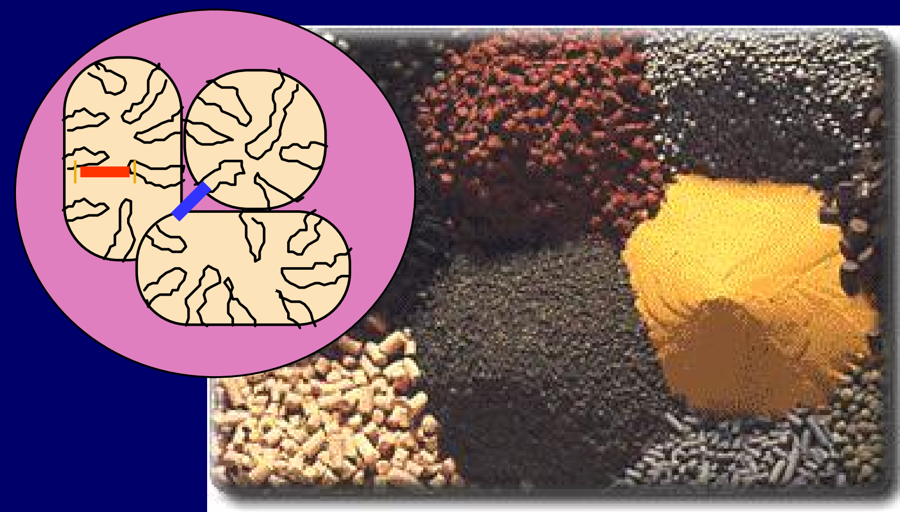
Diffusion across laminar streamlines (100<Re<2000)

Mass Transfer in Microchannels

Velocys | **Conventional**



vs.



~ 0.002 cm

~ 0.02 cm

~ 0.2-2 cm

~ 0.2 cm

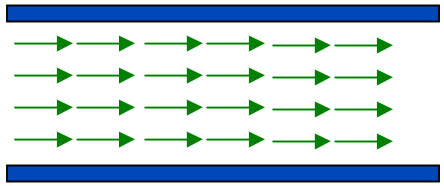
Velocys technology enhances both <u>intraparticle</u> and <u>interparticle</u> mass transfer

Low pressure drop

Laminar flow in microchannels

- Orderly flow – less fluctuations

$$\frac{\Delta P}{L} = f(D_h)\mu V_{flow}$$

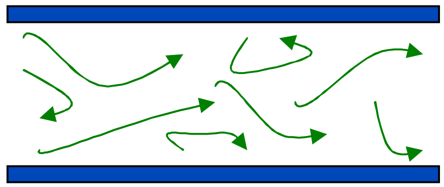


Turbulent flow

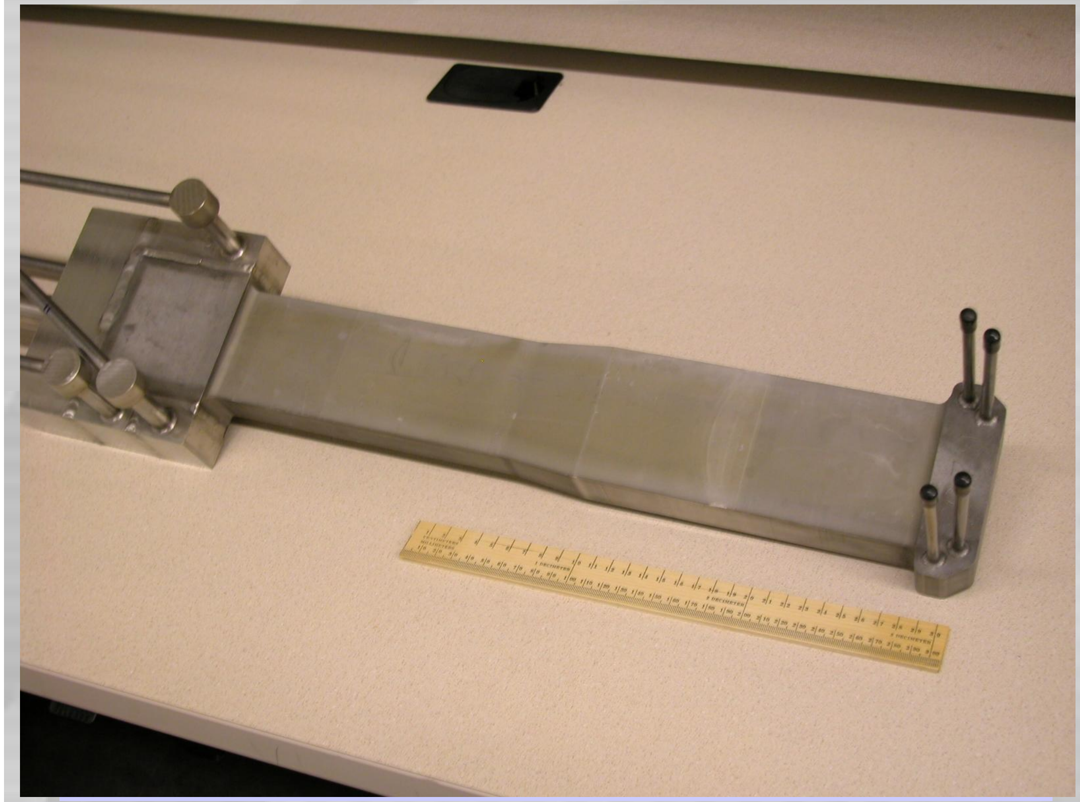
- Random flow – more fluctuations

- $$\frac{\Delta P}{L} = f(D_h)\mu^{0.25}\rho_{flow}^{0.75}V^{1.75}$$

(Blasius friction factor)



Pressure Drop Case Study



48 channel device

N_2, ambient

$Flow_{tot}$ = 40 SLPM

40” x 0.035” x 0.160”

Velocity = 4.2 m/s

Re = 391

DP = 1.47 psig (model)

DP = 1.51 psig (experimental)

Design for Reaction Applications

Design for Constraints

- Pressure Drop
- Temperature / Materials

Tailor Catalyst Form

- Match kinetics, heat removal, and pressure drop

Select Thermal Management Method

- Convective heat transfer
- Phase change
- Chemical reaction

Conventional Catalyst Technology

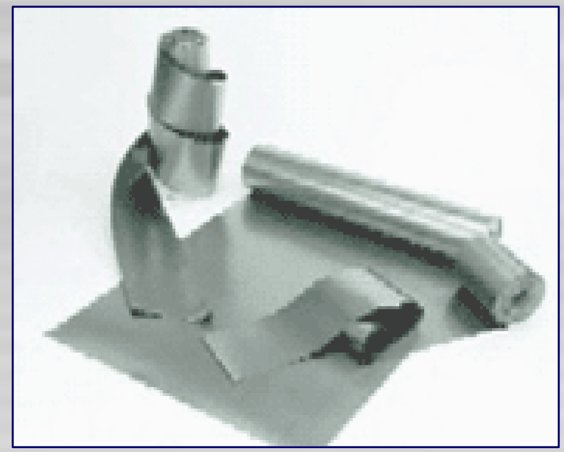
Powders for stirred tank or fluidized bed applications

Extrudates for fixed-bed applications

Monoliths for gas purification applications

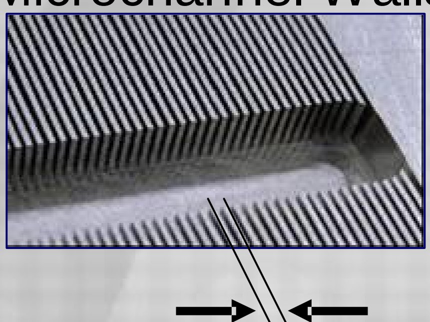
Catalysts for Microchannel Reactors

Porous Metallic Felts

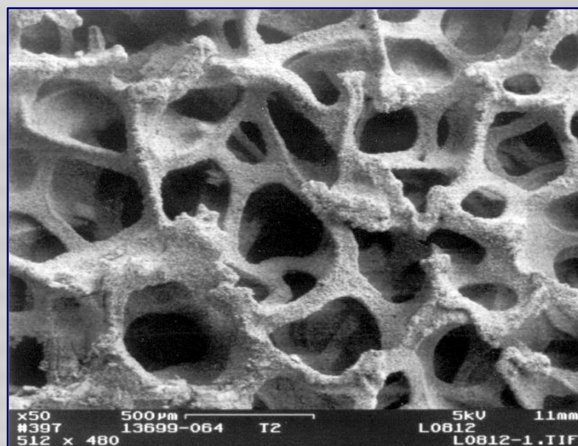


Metallic Foils

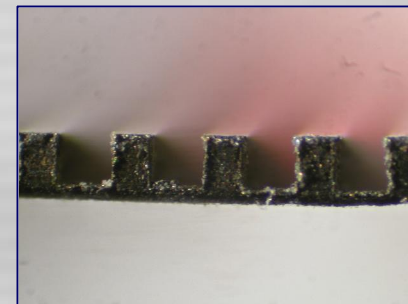
Microchannel Walls



~0.05-0.1 cm

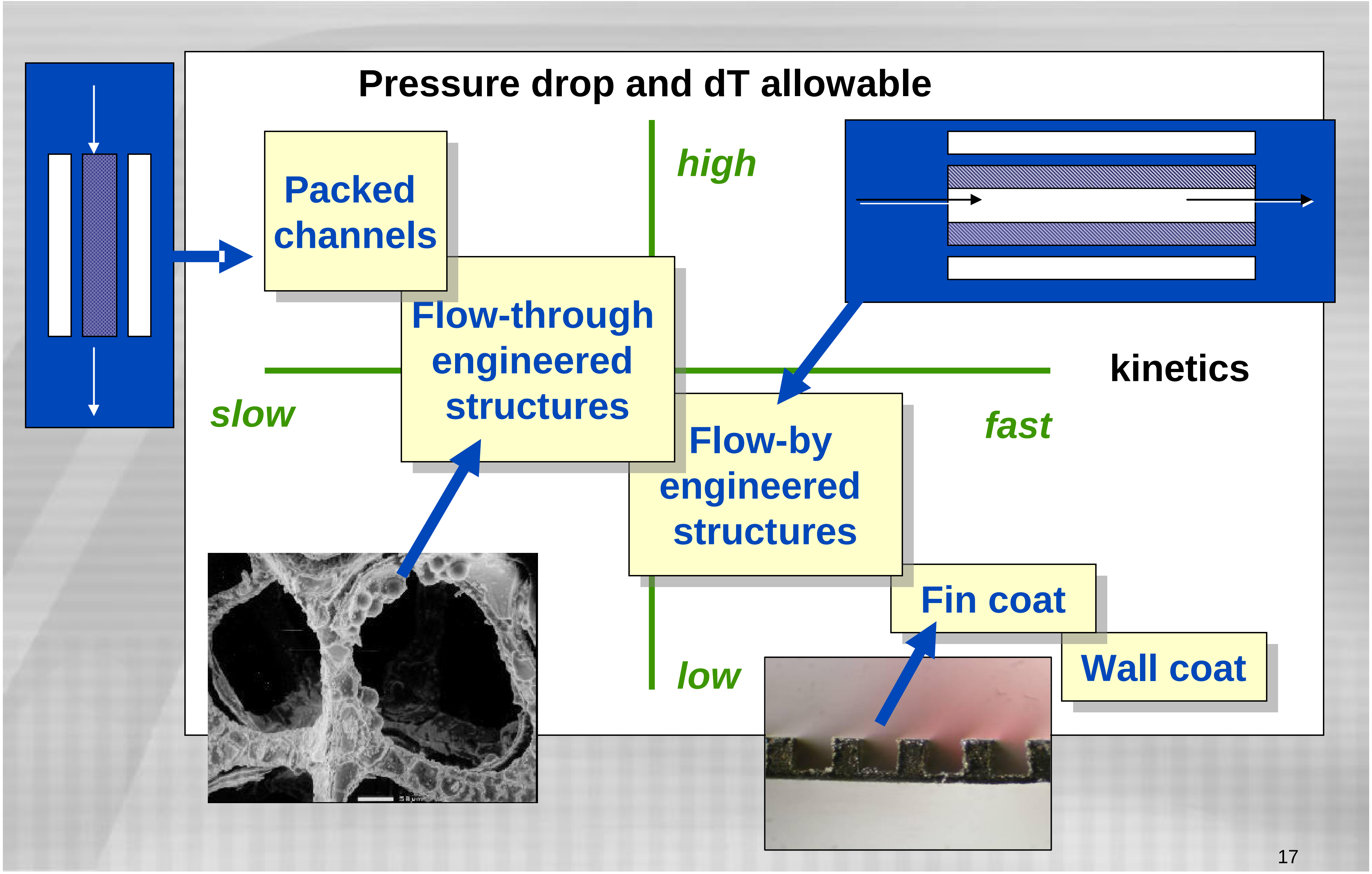


Metallic Foams

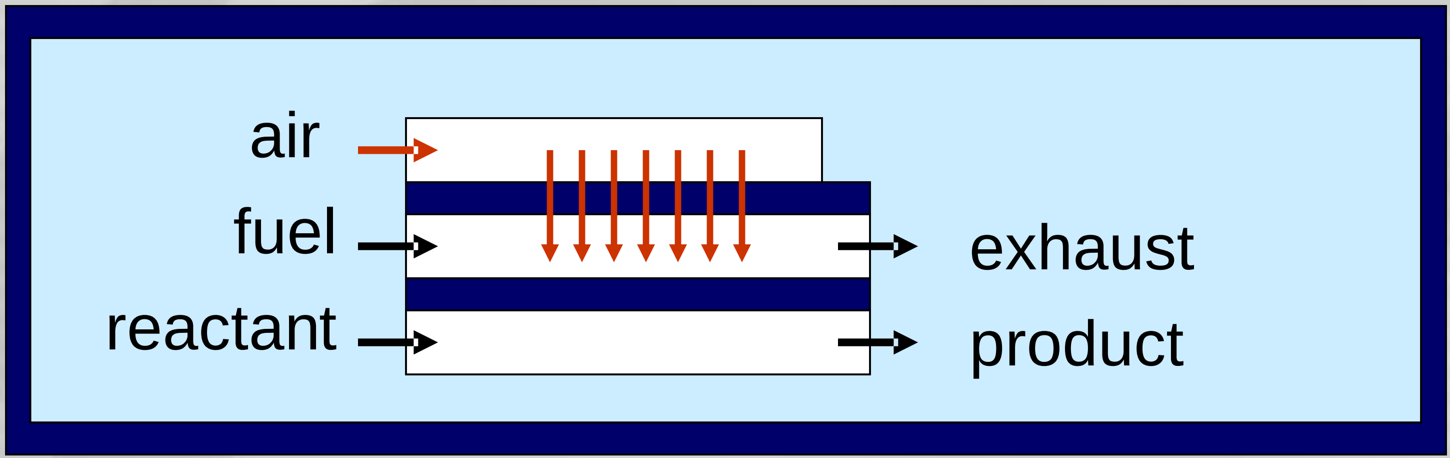


Metallic Fins

Catalyst Selection Strategy for Microchannel Reactors

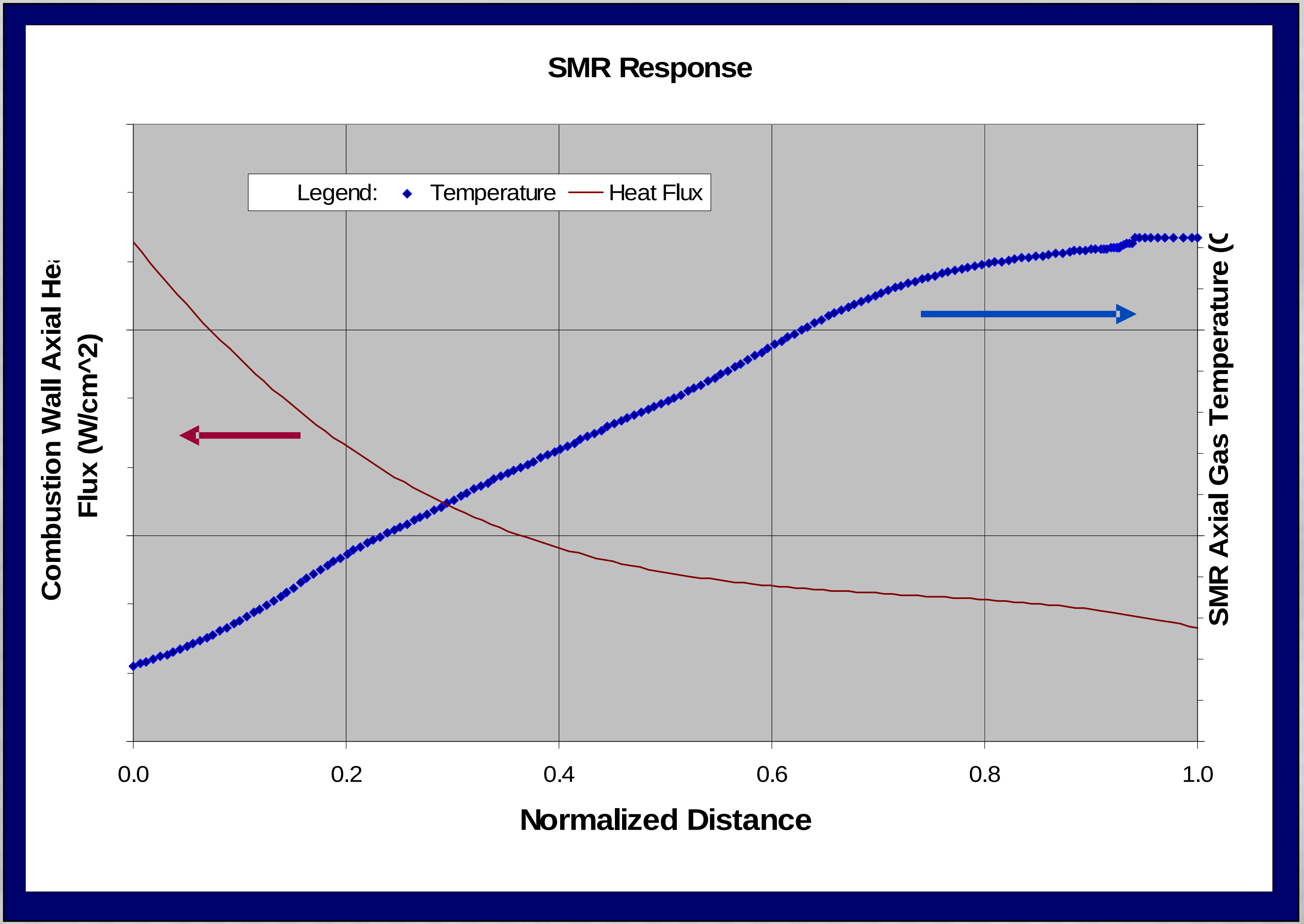


Endothermic Reaction Examples:
Tailor flux and thermal profile

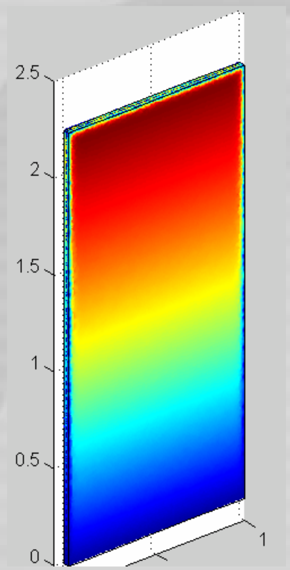


- Add heat by adjacent exothermic reaction
- Add heat by convective heat transfer
- Add heat by phase change

Thermal Performance: Endothermic Steam Reforming

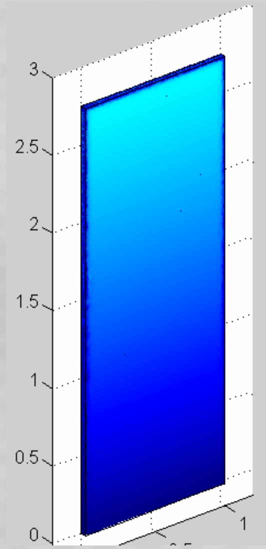


High Heat Transfer to Achieve Temperature Uniformity



Temperature profile down typical Fischer-Tropsch fixed bed reactor
Δ T ≧ 25 C

Temperature profile down fixed bed Fischer-Tropsch microchannel
Δ T ≈ 2 C



Velocys Technology Applications

Reactions

Methane Reforming | *Fischer-Tropsch*
Oxidation | *Methanol*
Dehydrogenation | *Reactive-Distillation*

Separations

Thermal swing adsorption | *Distillation*

Mixing

Emulsions

Heat Exchange

Compact Heat Exchangers | *LNG*

Scale-up

- Manufacturable and Cost Effective Design
- Sufficient Flow Distribution
- Robust Operation
- Integration with Commercial Plants

Velocys Scale-up Methodology

Cell

- Internal channel dimensions same as commercial chemical processor
- Number of channels increase; size of channels does not

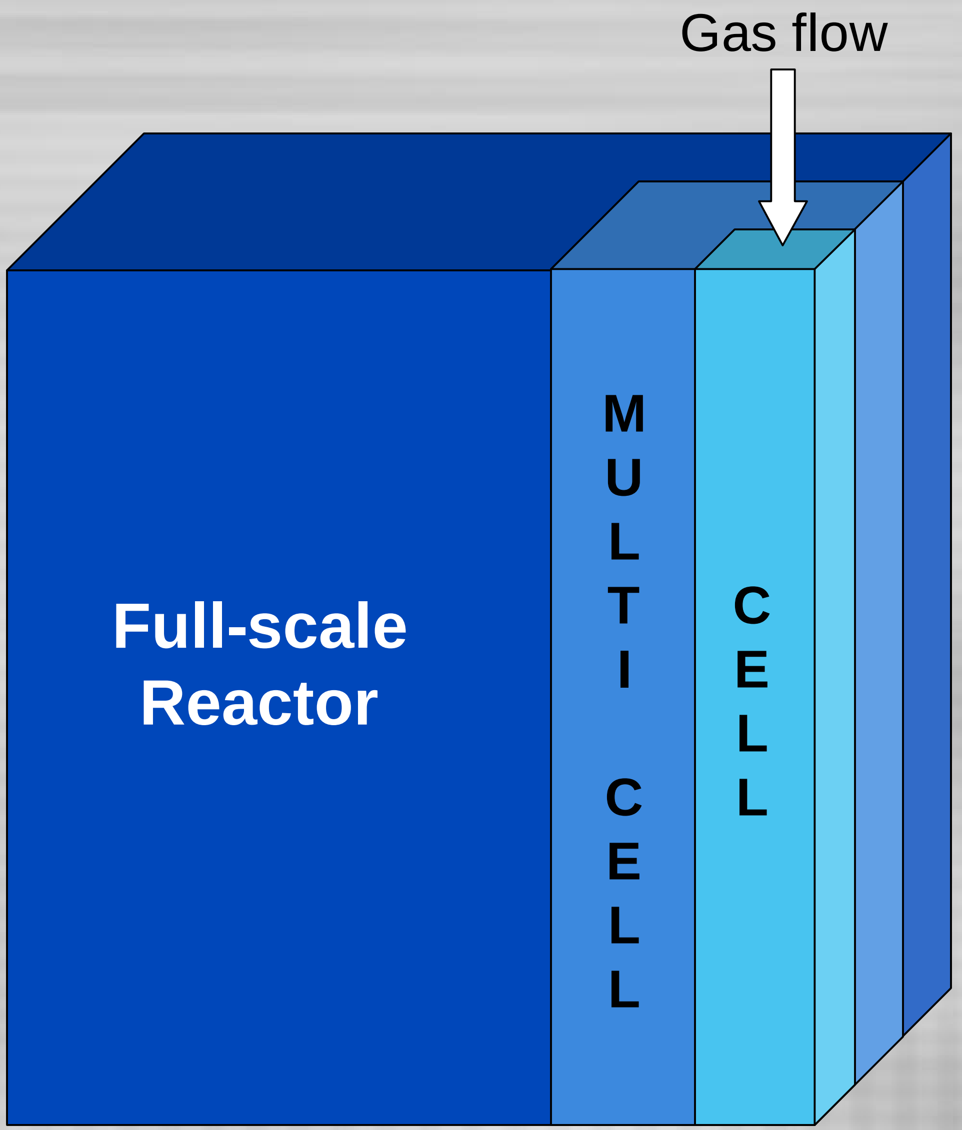
Multi-Cell

- Many channels
- 10-100 lb/hr

Full-Scale

- >1000 channels
- 1000-5000 lb/hr

Full-Scale Reactor is the basic building block of a commercial plant



Commercial Microchannel Reactor:
Summary for Hydrogen Generation

Productivity
- 1MM SCFD H_2 per reactor

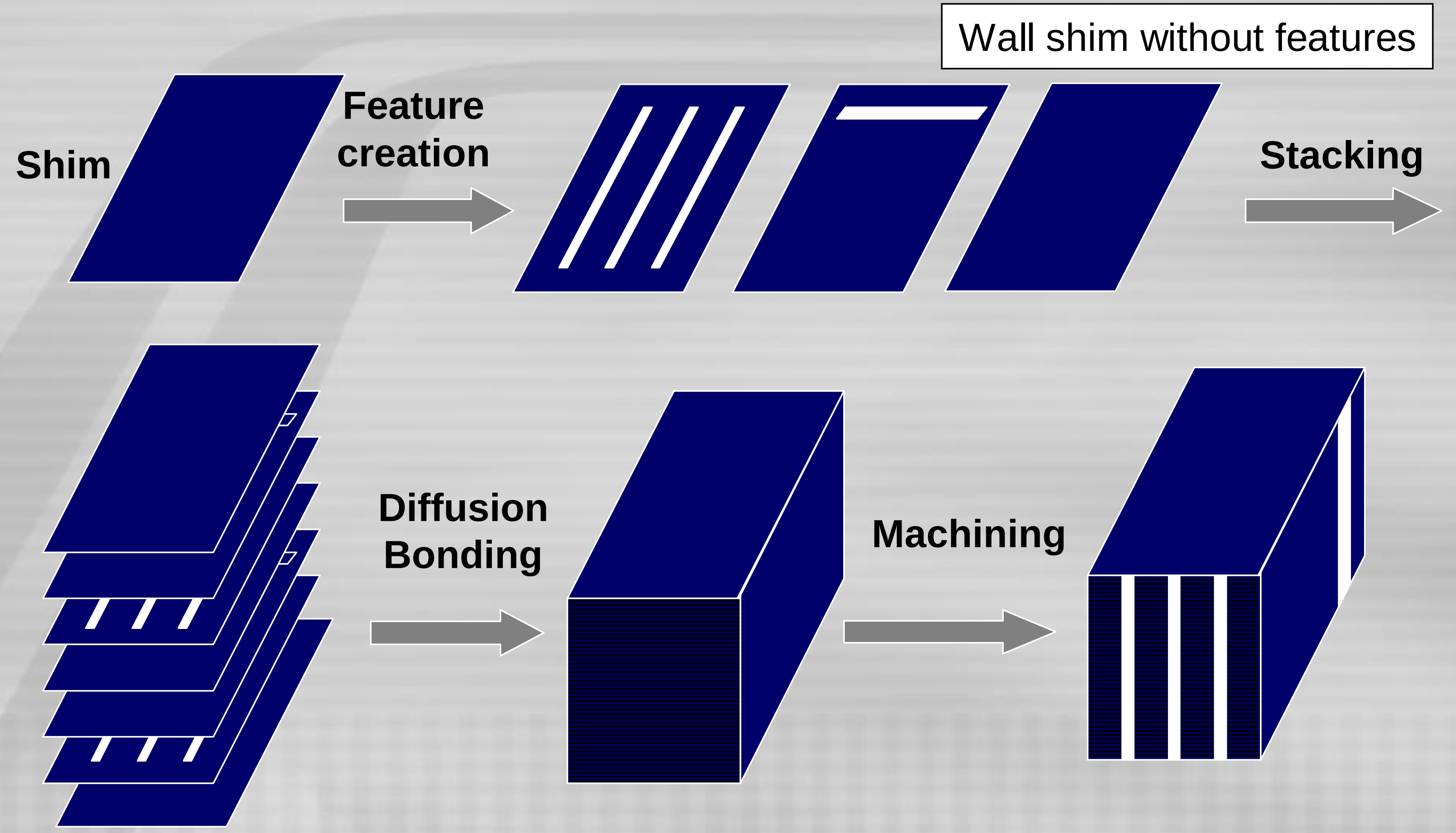
Size
- ~0.6 m x 0.8 m x 0.6 m
- 2 tons
- >5000 channels

Streams
- Air ~70 ºC
- Fuel ~70 ºC
- Reactant ~200 ºC
- Product ~300 ºC
- Exhaust ~300 ºC

Emissions
- NO_x < 10 ppm
- Meets California regulations

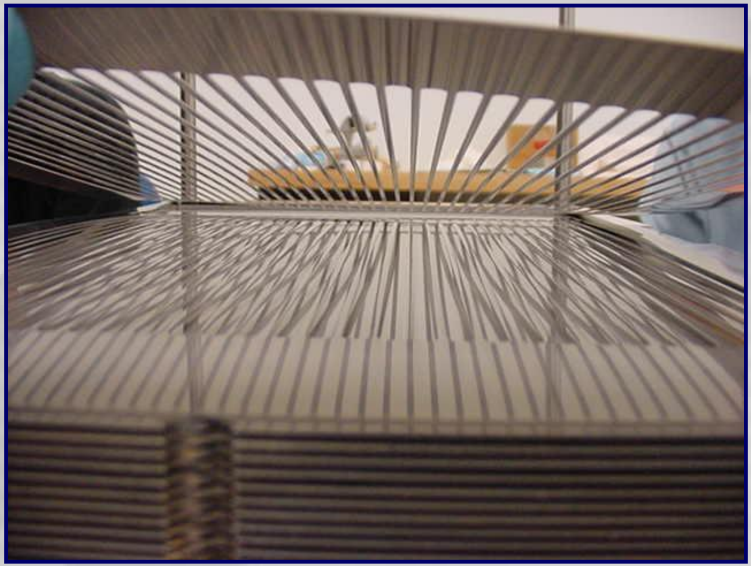
Eighth-scale Device

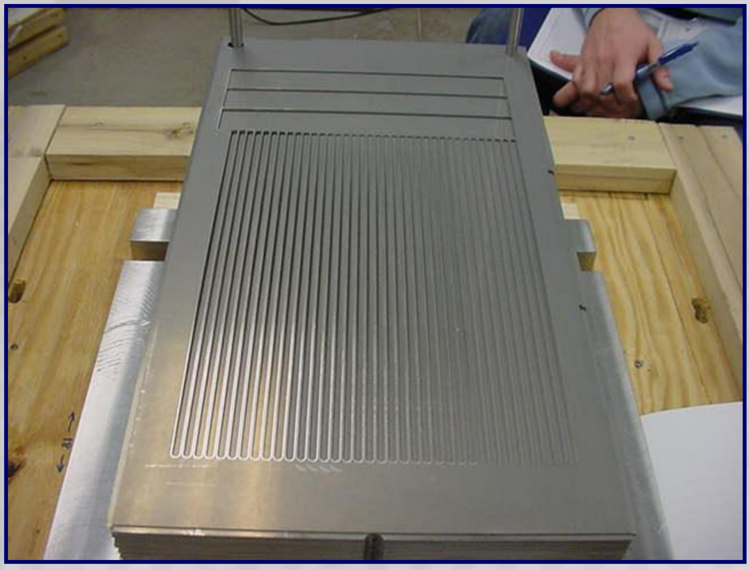
Manufacturable Design:
Metal thinness creates microchannel dimension



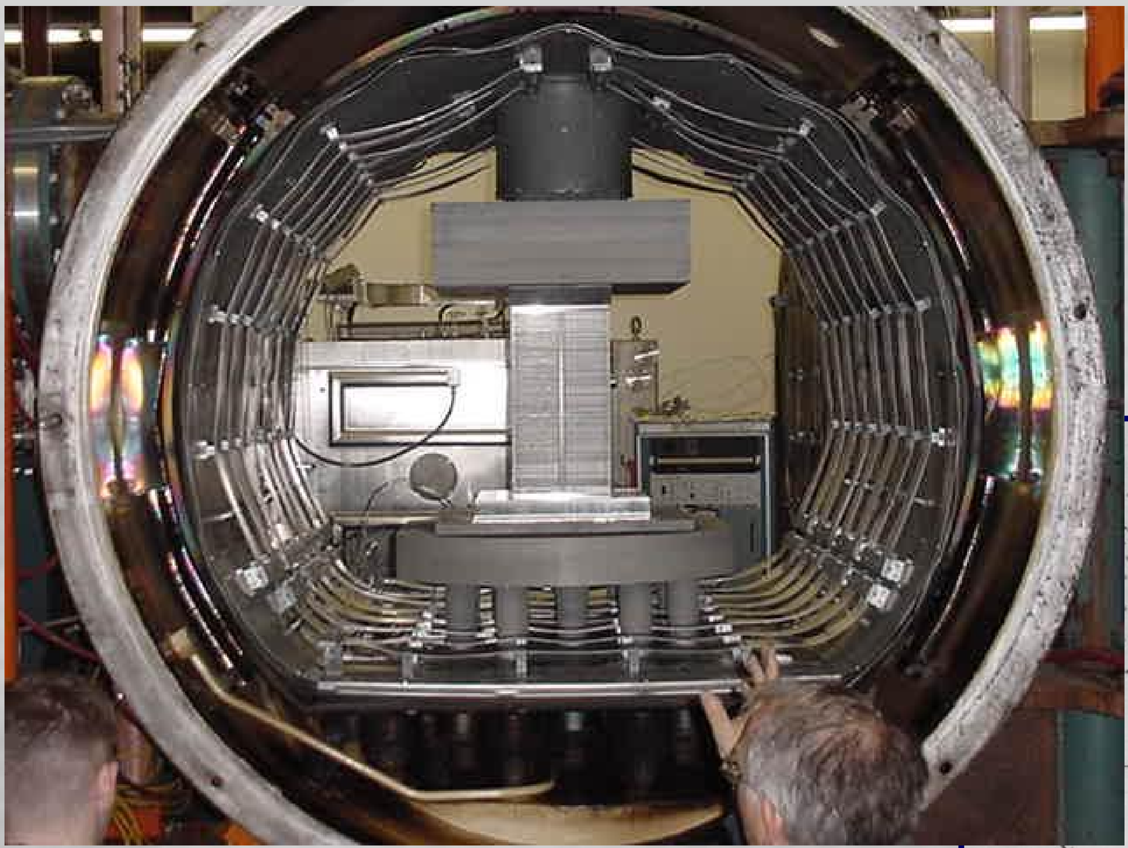
Bonding creates hermetically sealed microchannels

Device Manufacturing



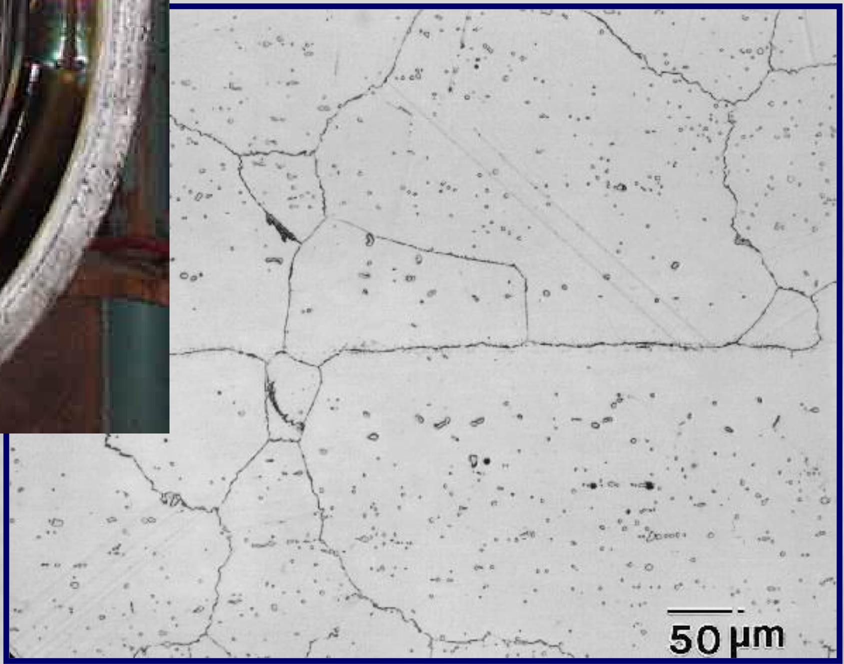


Diffusion Bonding Large Stacks



<u>Protocol</u>

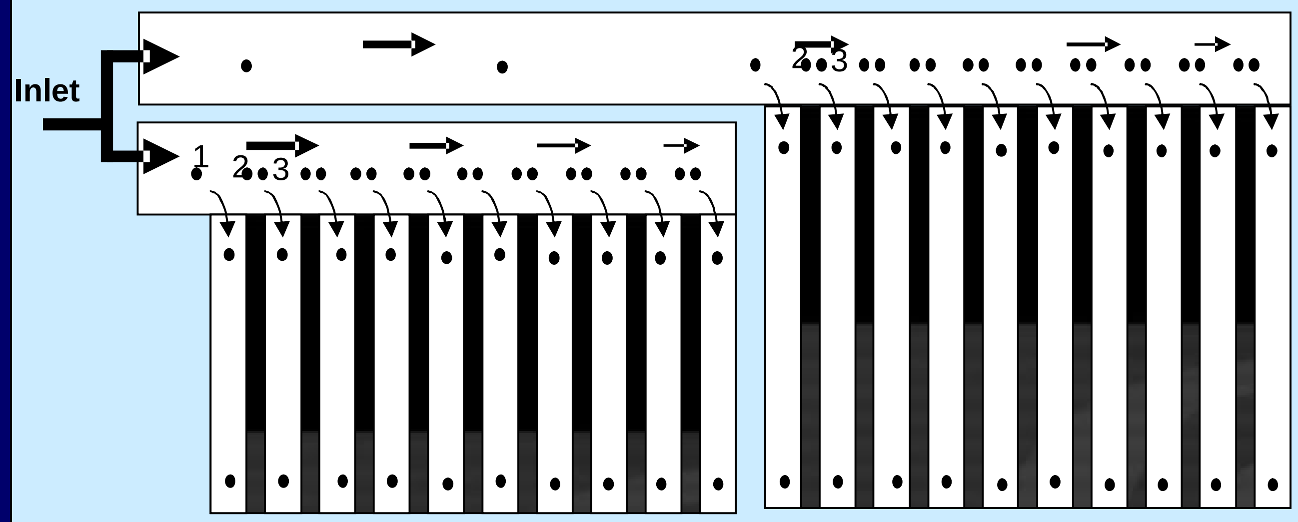
- Time
- Temperature
- Pressure



Scale-up Considerations

- Manufacturable and Cost Effective Design
- Sufficient Flow Distribution
- Robust Operation
- Integration with Commercial Plants

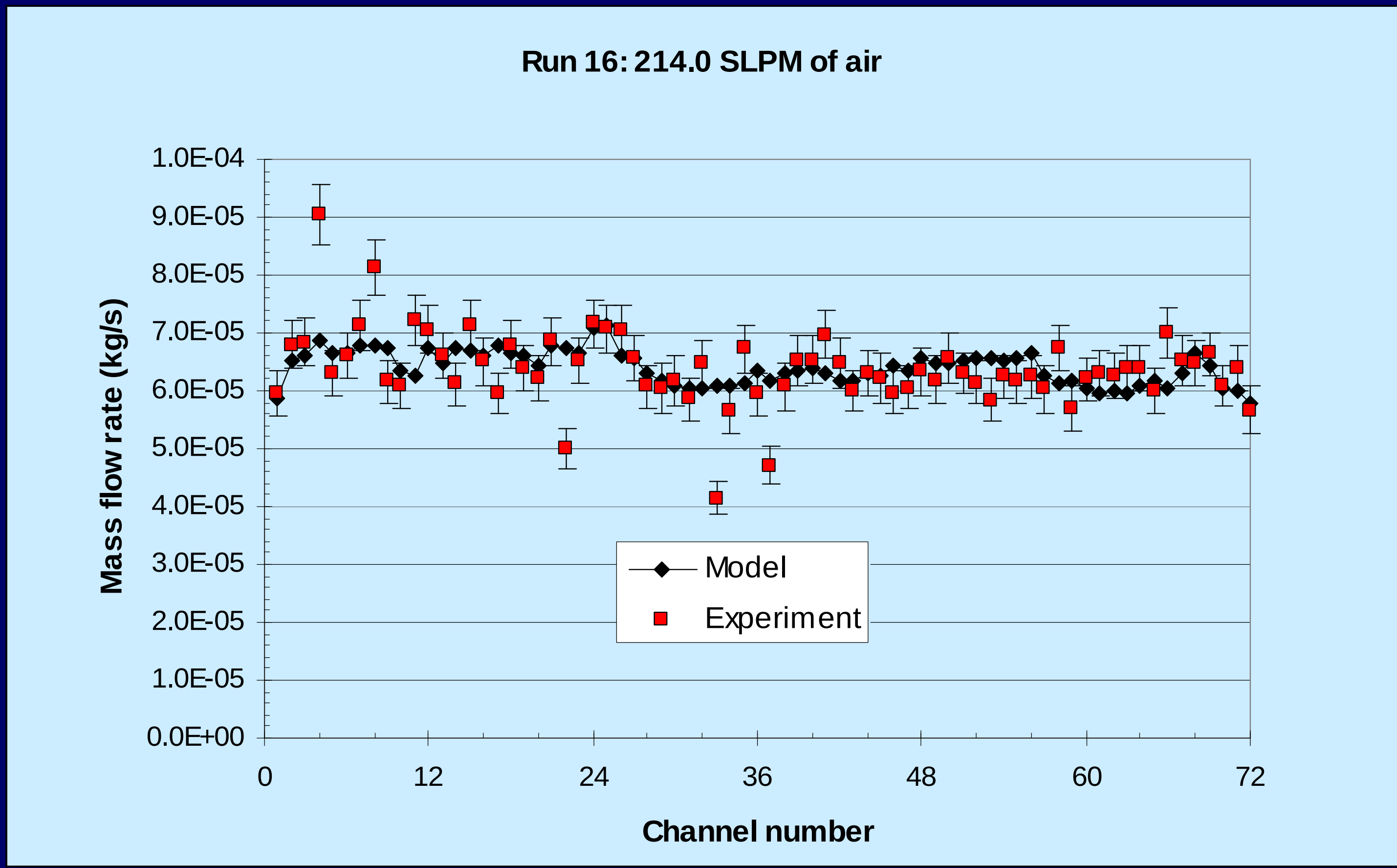
Tailor Pressure Drop in Flow Circuits
To achieve sufficient flow distribution



$$Q_1 = \frac{m_{\max} - m_{\min}}{m_{\max}} \times 100\%$$

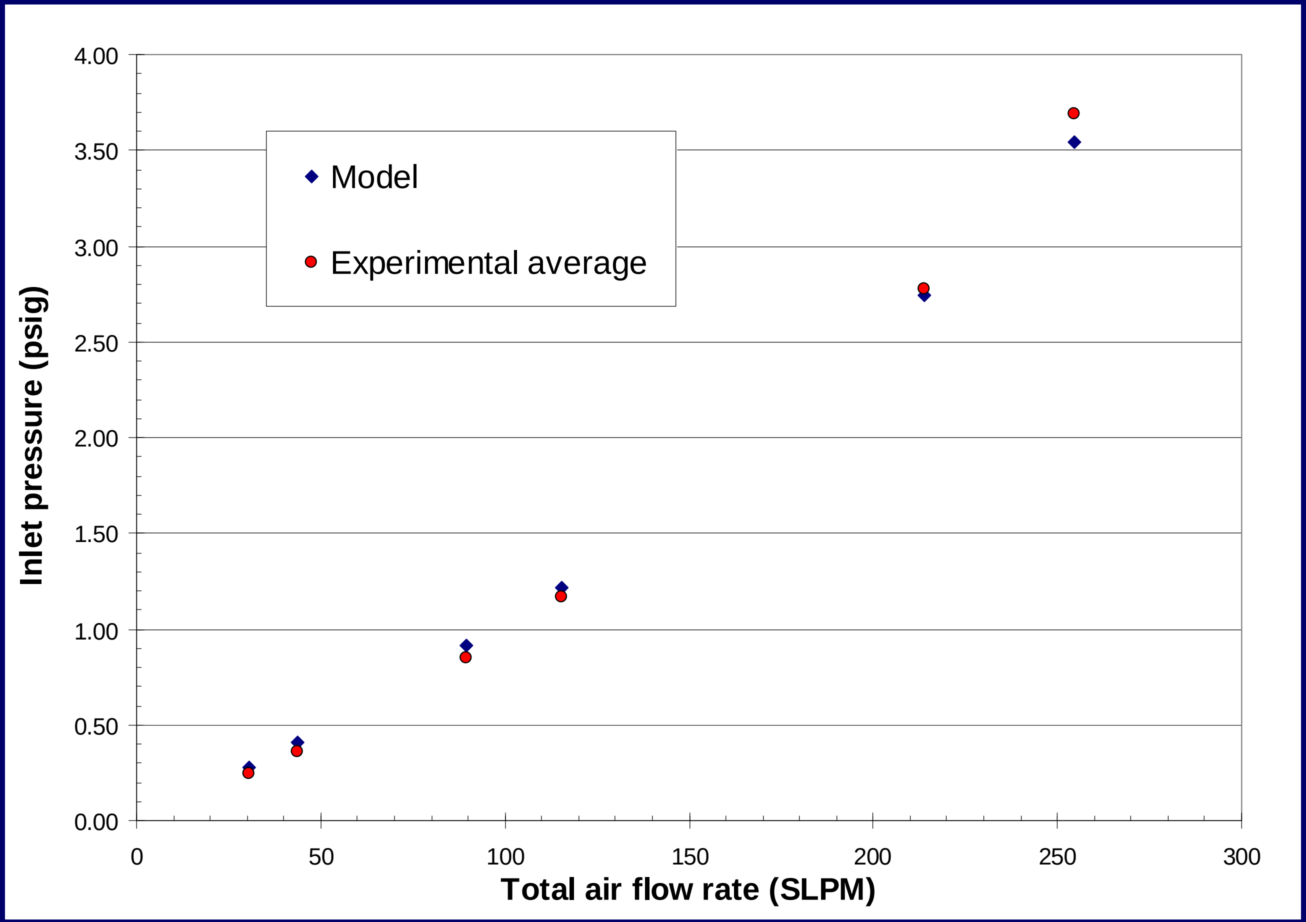
Flow Distribution Validation

Channel Flow Distribution



Sufficient flow distribution measured in test device

Manifold Model vs. Experiment dP



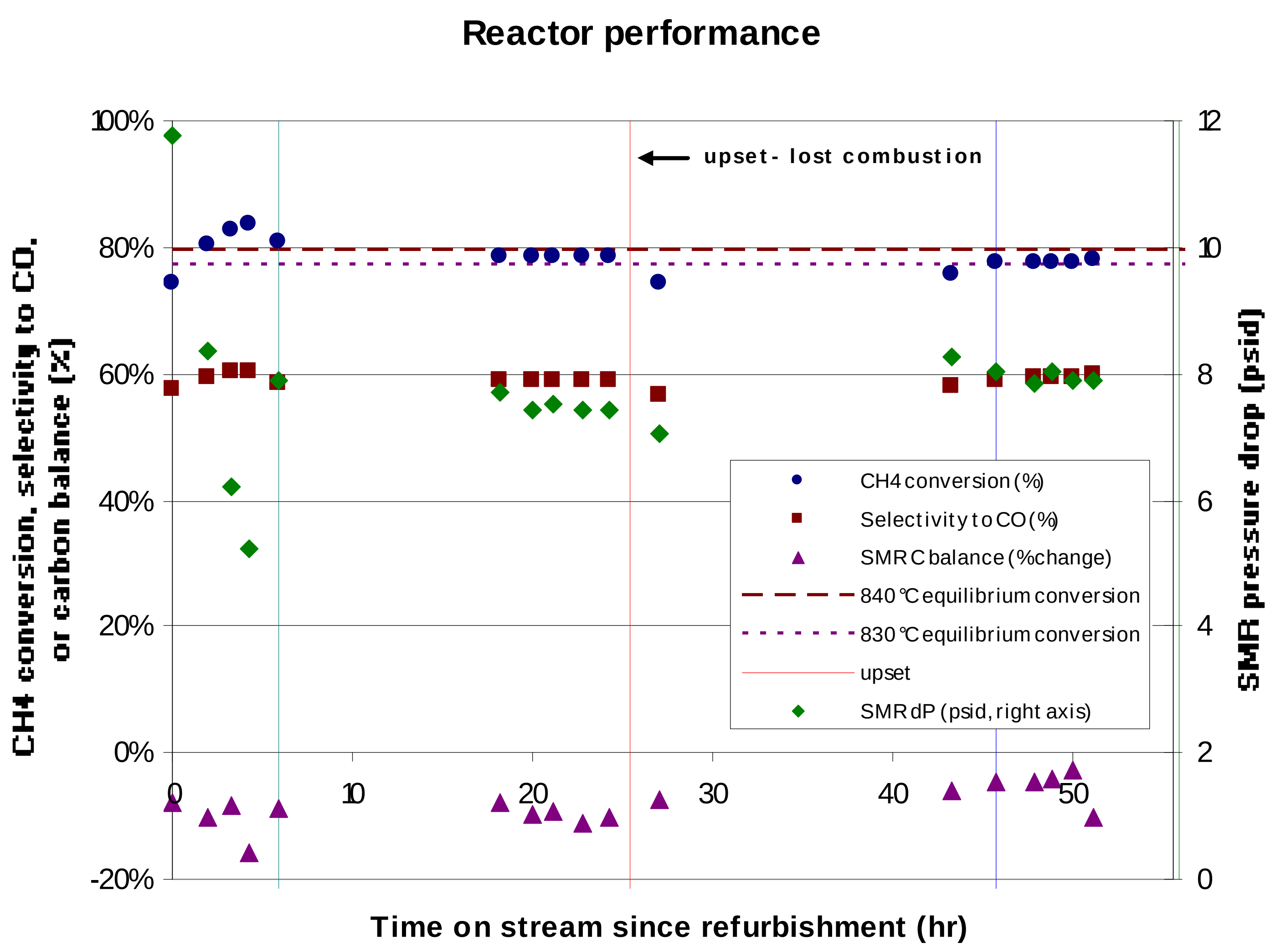
Predicted manifold pressure drop matches experiments

Scale-up Considerations

- Manufacturable and Cost Effective Design
- Sufficient Flow Distribution
- Robust Operation
- Integration with Commercial Plants

Robust Performance to Upsets

Recovery after combustion lost and catalyst *in situ* refurbishment



<u>Conditions:</u>

3:1 S:C

23 atm

6 ms CT

9000 scfd H_2

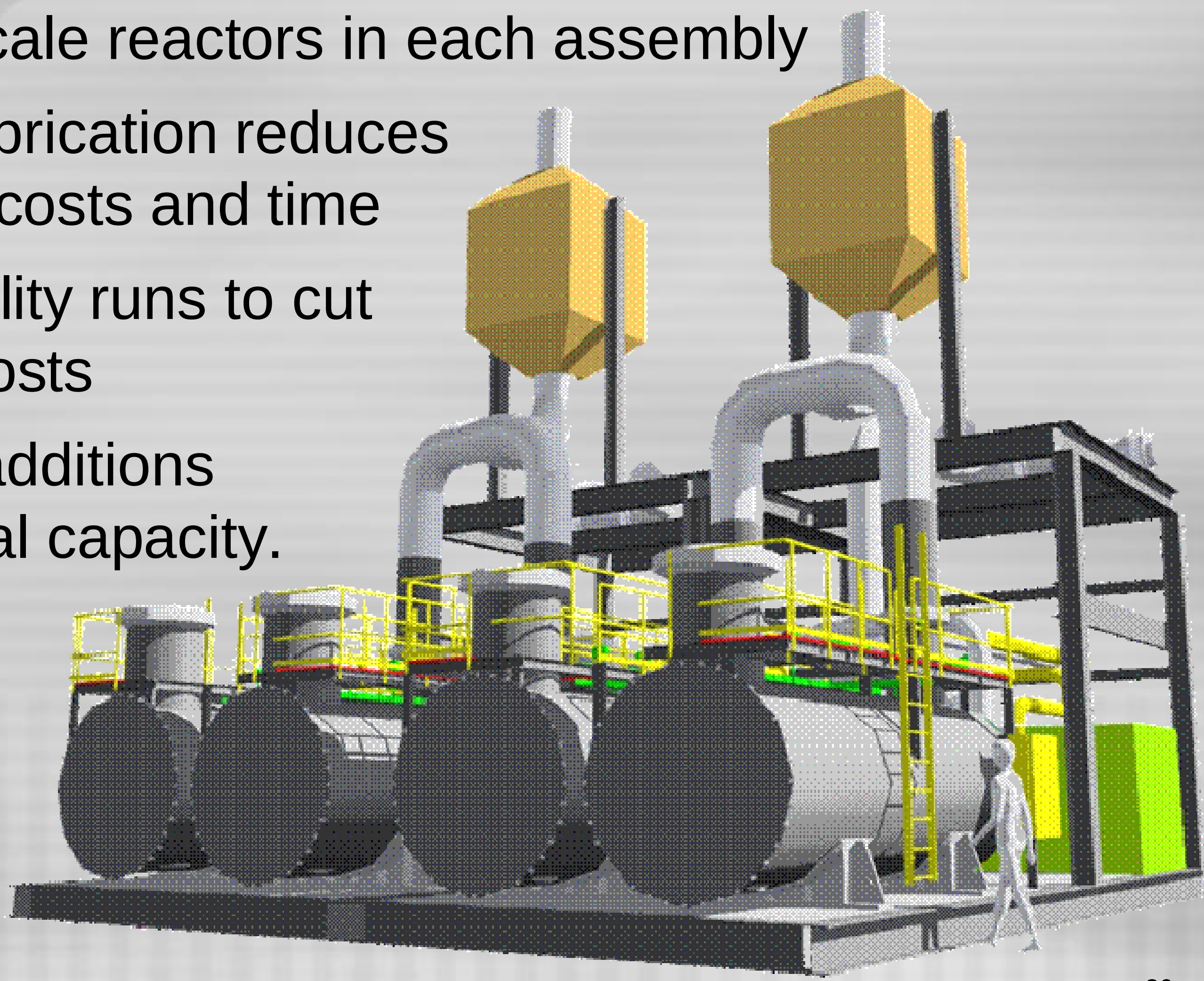
Scale-up Considerations

- Manufacturable and Cost Effective Design
- Sufficient Flow Distribution
- Robust Operation
- Integration with Commercial Plants

Microchannel Reactor Plant Interface

Low-cost standardized reactor assemblies:

- 5 to 30 full-scale reactors in each assembly
- Shop-built fabrication reduces construction costs and time
- Minimizes utility runs to cut installation costs
- Modular for additions of incremental capacity.



Summary

Microchannel technology's advantages

- Tailored thermal profiles
- Optimized catalyst performance and form
- Enhanced selectivity
- Higher productivity
- Operation near stoichiometric feed ratio

Model driven design and optimization process

Scale-up principles modeled and validated

Contact Information

Dr. Jan J. Lerou
Manager, Experimental Operations
Velocys Inc.
7950 Corporate Blvd.
Plain City, OH 43064
Phone: (614) 733-3300
Email: lerou@velocys.com

www.velocys.com