

# Heterogeneous Catalysis: Nanoscale Meets the Atomic Scale

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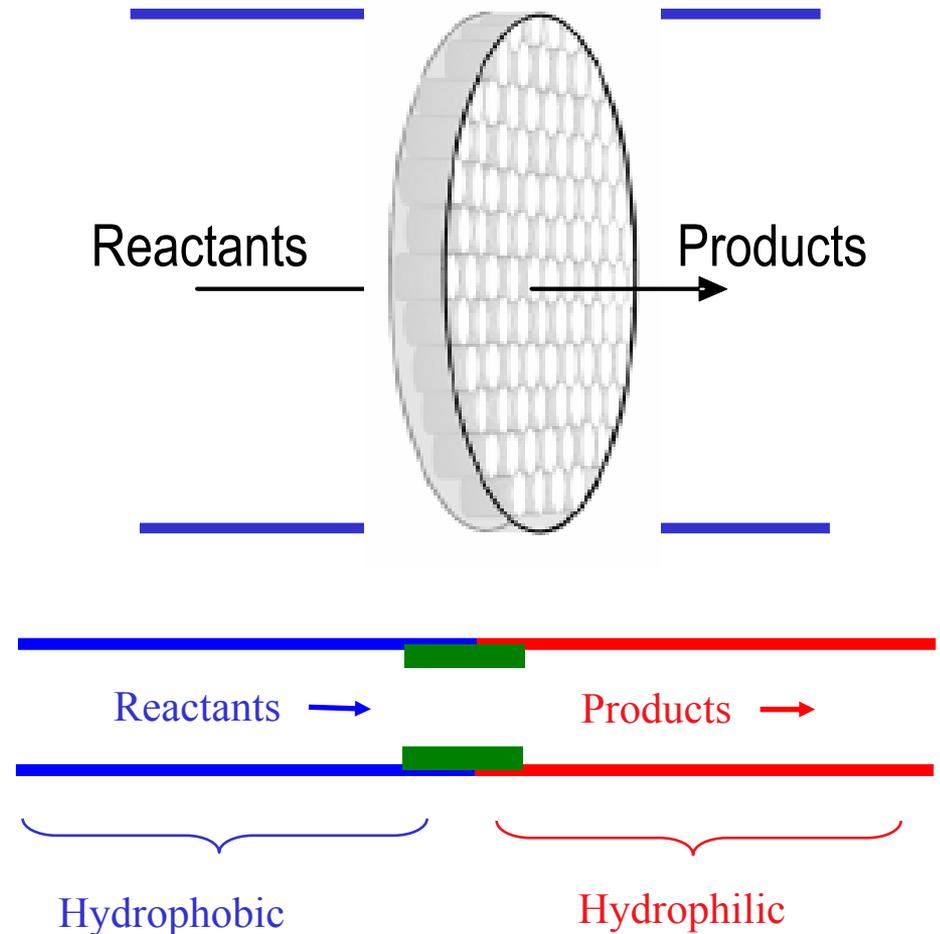
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# Uniform Nanostructured Membrane Catalyst

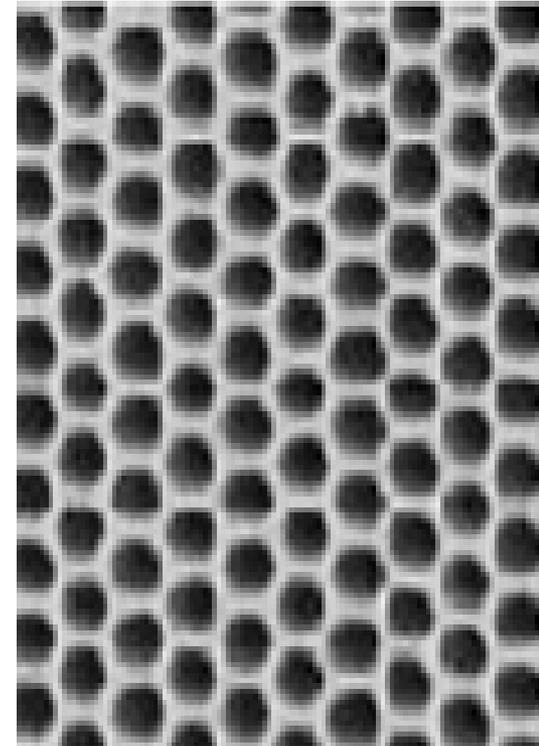
- **Uniform Pores**
  - Nanoreactor Array
- **Contact Control**
  - Identical Diffusion Paths
  - Contact Time Control
- **Reagent Size Control**
  - Pore-size Selection
- **Site Isolation**
  - One Particle in Each Pore
  - No Sintering
- **Sequenced Sites**
  - Sequence Particles Along Pore



# Anodic Aluminum Oxide (AAO) Membranes



100 nm pores

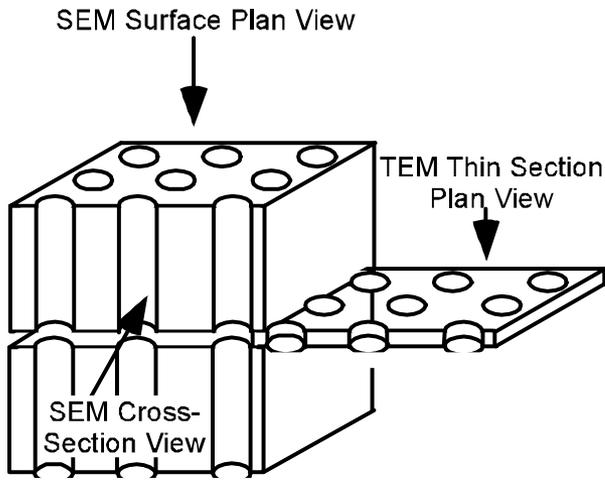
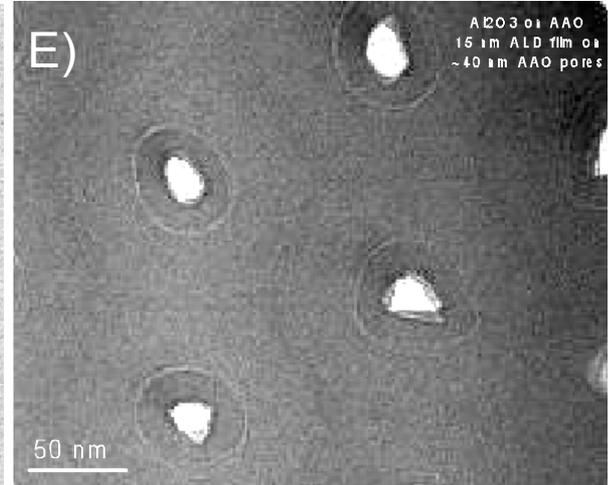
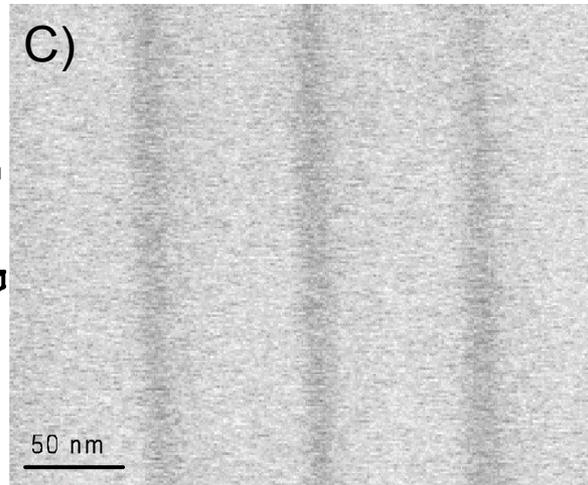
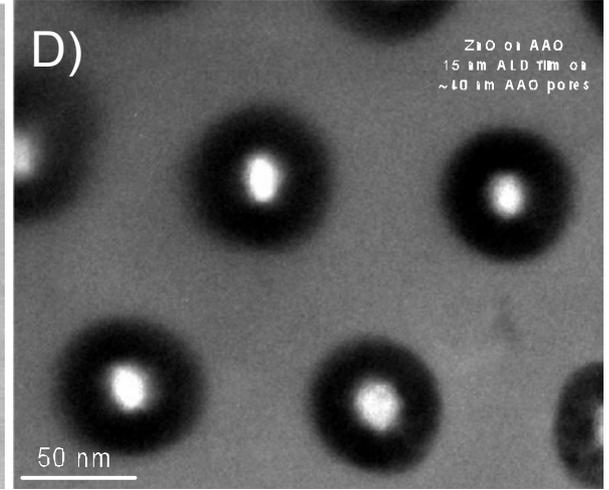
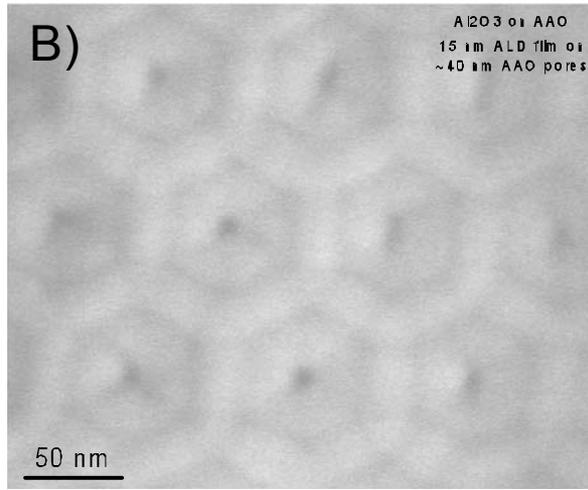
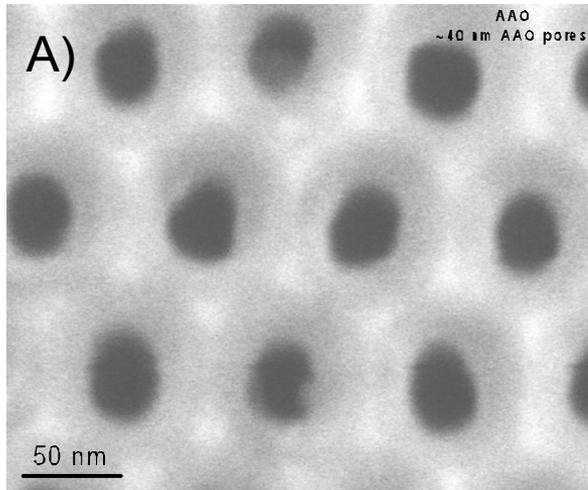


- $10^{10}$  pores
- Stable  $> 550^{\circ}\text{C}$
- $\Delta P > 10$  psi
- Flow  $> 10$  sccm

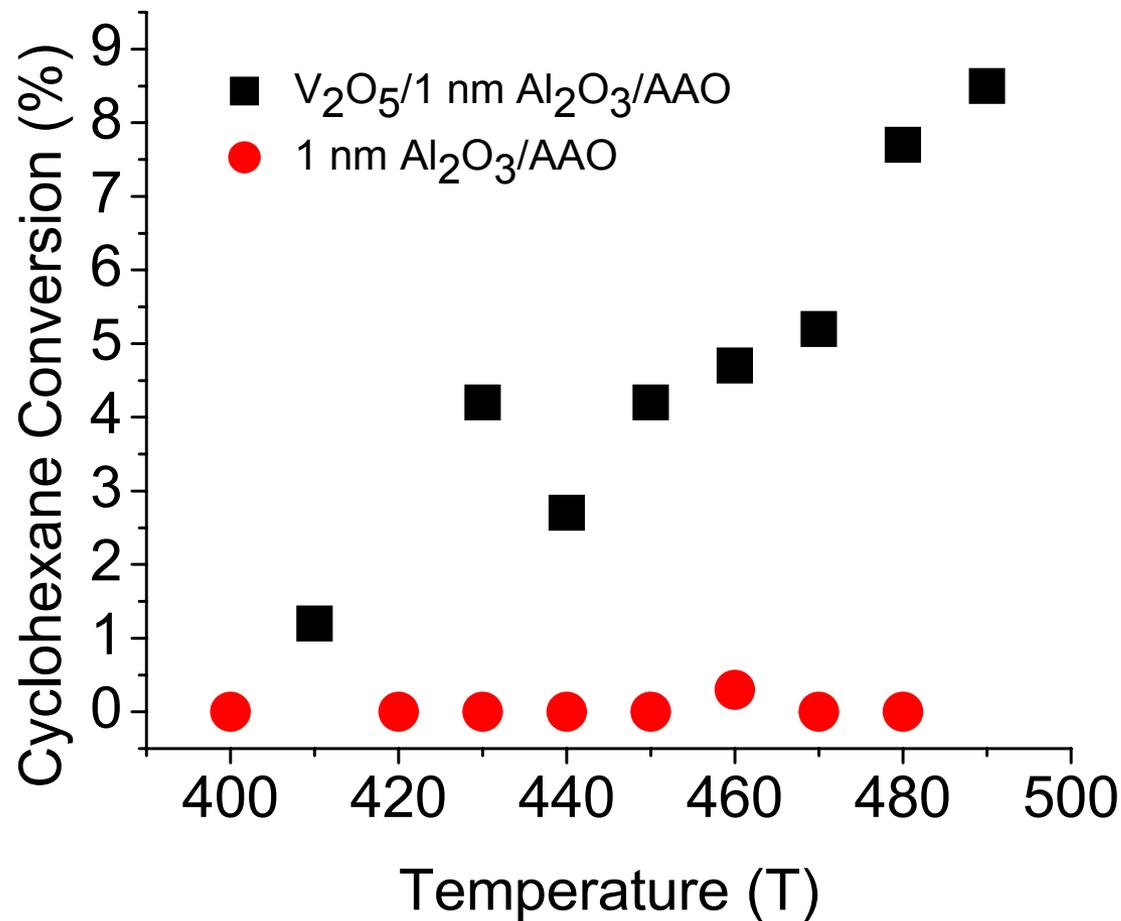
**AAO made in 0.3M oxalic acid**



# Pore Wall Control: Atomic Layer Deposition



# Cyclohexane ODH



# Opportunity: Uniform, Isolated Catalytic Particles

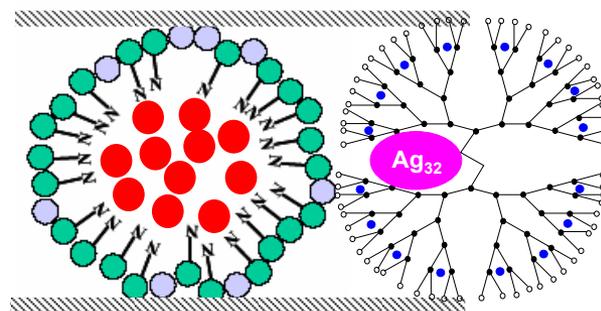
## Pore Impregnation

$$\text{Volume} = 10^{-15} \text{ cm}^3$$

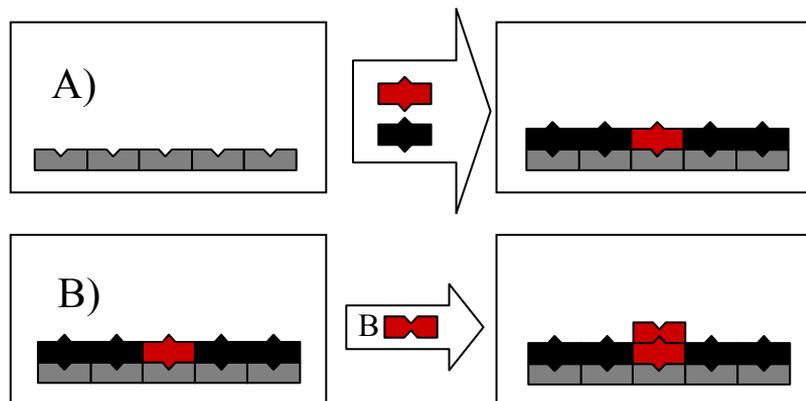
.01 M solution  $\Rightarrow$  7,500 atoms

$\Rightarrow$  One 5-nm particle

## Nanoparticles in Pores



## ALD Particle Synthesis



## Massively Parallel Combinatorial



# *X-ray and Neutron Challenges*

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- **Single Particle Characterization**
  - Metals and Compounds
  - Structure
  - Composition
  - Dynamics
  - Chemistry
- **Catalysis Grand Challenges**
  - Selective Catalytic Oxidation of Hydrocarbons
    - *Endothermic -> Exothermic*
  - 100% Selectivity
    - *ca. 15% of Industrial Energy Consumption*