# An Intermediate Temperature Direct Ammonia Fuel Cell

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Ammonia - A Sustainable, Emission-Free Fuel
October 15, 2007

# Why Fuel Cells?

- **Pros:**
  - **High chemical-to-electric efficiency (45-80%)**
  - **No moving parts (quiet, low/no maintenance)**
  - **High energy density (limited only by size of fuel tank)**
  - **Cell is usually lightweight**
  - **Systems are inherently scalable**
- **Cons:**
  - **Expensive! (catalyst costs, housing costs, electrolyte costs)**
  - **Often limited by fuel type or purity of fuel & fuel byproducts**
  - **Limited power density (difficult to get energy delivered quickly)**
  - **Balance of plant may be costly/heavy/problematic**
- **So, how do we maximize the "pros" and limit the impact of the "cons?"**

# Focus Areas

- **Cons:**
  - **Expensive! (catalyst costs, housing costs, electrolyte costs)**
    - **Catalysts and housing: impacted by operating temperature**
    - **Electrolyte: Fuel cell type (op. temperature, again)**
  - **Often limited by fuel type or purity of fuel & fuel byproducts**
    - **Compatibility with electrocatalysts: proper fuel choice**
    - **Direct fuel & avoiding catalyst poisoning: op. temperature**
  - **Limited power density (difficult to get energy delivered quickly)**
  - **Balance of plant may be costly/heavy/problematic**
    - **Reducing HX sizes: operating temperature**
    - **Fuel reservoir size or delivery of fuel: proper fuel choice**

# Step 1: Use the Right Fuel

CH4 103 (1.5 H2)

$$2\ NH_3 \longrightarrow 3\ H_2 + N_2 \qquad \Delta H^\circ = 46\ kJ/mol$$

- Very mild enthalpy of reforming
- $NH_3$ is a liquid at room temperature and 10 bar
  - Power density is comparable to other liquid fuels
  - Vaporizes when throttled (no flash line required)
- Essentially non-flammable, non-explosive
- 171 kWh of motive power from 15 gallons ammonia (38 kg) with 48% efficient fuel cell system incl. motor
- Highway driving: 19 kW; yields 9 hours of cruising
- 65 miles per hour takes you 585 miles
- **Ammonia makes that possible**

356 kWh nom
150 mi gas

# Step 2: Operate at the Right Temperature

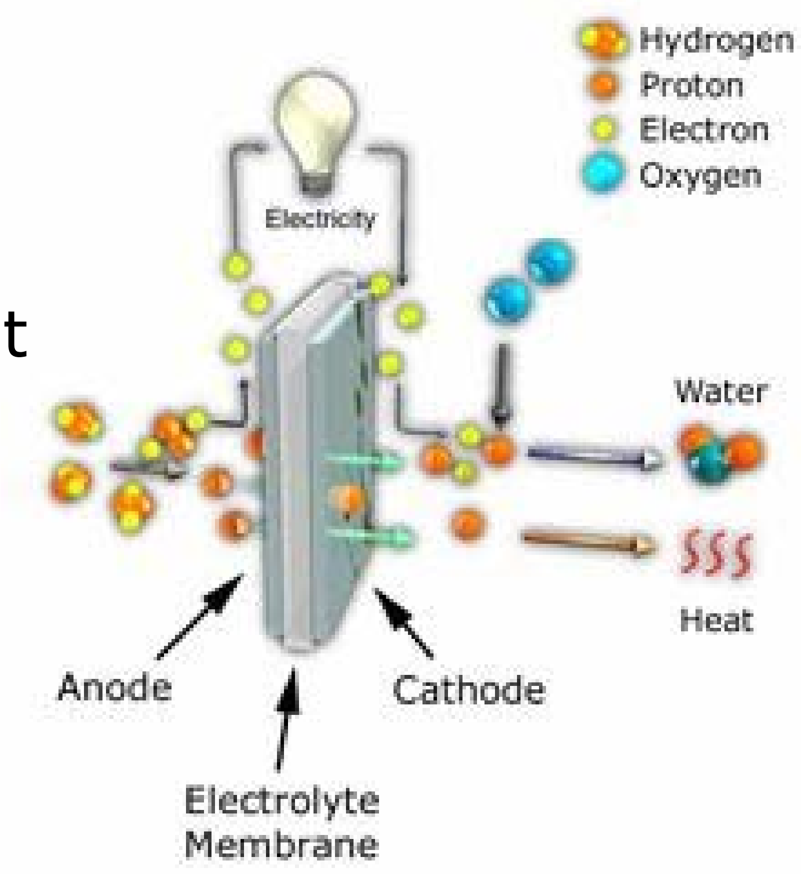
- **Low Temperature Fuel Cell Advantages**
  - Quick start-up to operating temperature (~100°C)
  - Wide range of cell construction materials
- **High Temperature Fuel Cell Advantages**
  - Fuel flexibility via internal fuel reforming
  - Inexpensive, base metal electrocatalysts
  - Easier heat recovery for increased efficiency
- **Intermediate Temperature Fuel Cells: The Best of Both Worlds?**
  - Precious metal catalysts not needed above ~300°C
  - Steel internals may be used below ~500°C

# Contemporary Fuel Cell Options

- Polymer Electrolyte Membrane Fuel Cells (PEMFC) [80°C, $H^+$]
- Alkaline Fuel Cells (AFC) [80-150°C, $OH^-$]
- Phosphoric Acid Fuel Cells (PAFC) [220°C, $H^+$]
- [Intermediate Temp Fuel Cell, 300 - 500°C]
- Protonic Ceramic Fuel Cell (PCFC) [600°C, $H^+$]
- Molten Carbonate Fuel Cells (MCFC) [650°C, $CO_3^{2-}$]
- Solid Oxide Fuel Cells (SOFC) [800°C, $O^{2-}$]

# PAFCs / PEMFCs and Ammonia

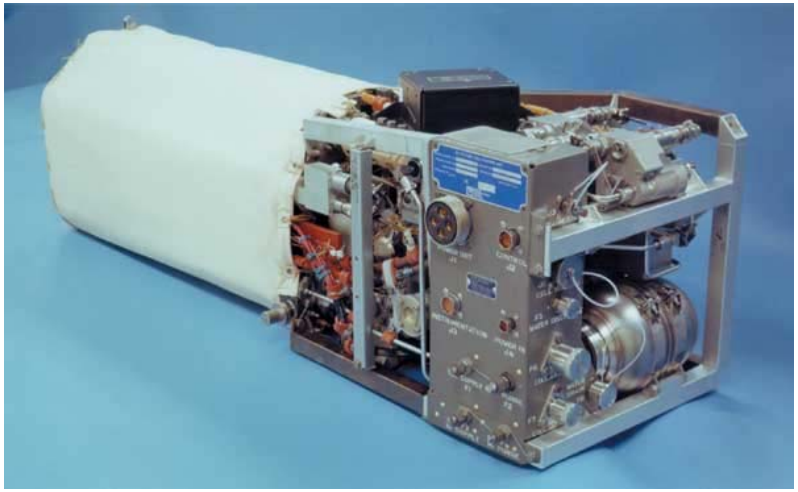
- **External $NH_3$ reforming required**
  - Trace $NH_3$ poisons acid membrane
  - Even well-reformed fuel must be scrubbed
- **Temperature and humidity issues**
  - Above 100°C, membrane dries out, loses conductivity
  - Inefficient heat recovery
  - Precious metal electrocatalysts required




*Plug Power Inc.*

# Alkaline FCs and Ammonia

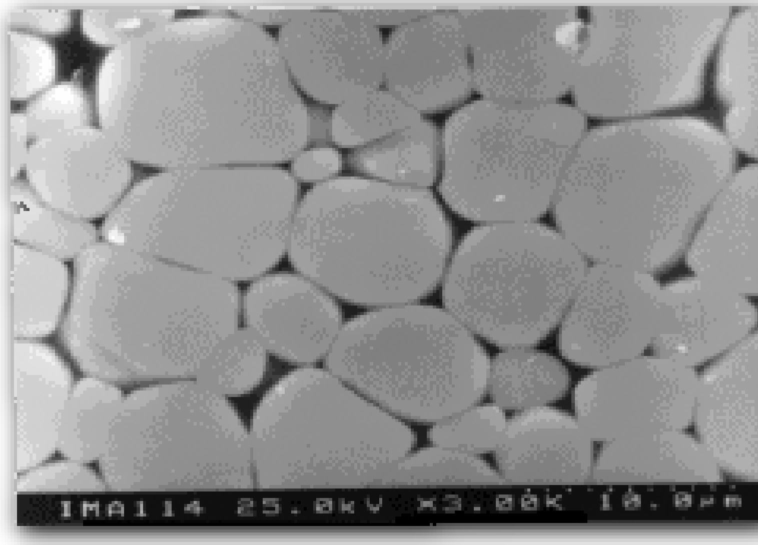
- **AFCs are tolerant of residual $NH_3$**
  - Still must crack $NH_3$ externally
  - Precious metal catalysts
- **Lifetime issues**
  - Corrosive electrolyte
  - Intolerant of $CO_2$
    - Formation of carbonate precipitates
    - Fuel and air streams must be purified



*United Technologies*

# The PCFC and Ammonia

- **PCFC / $NH_3$ is a good match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Ni/cermet electrocatalysts

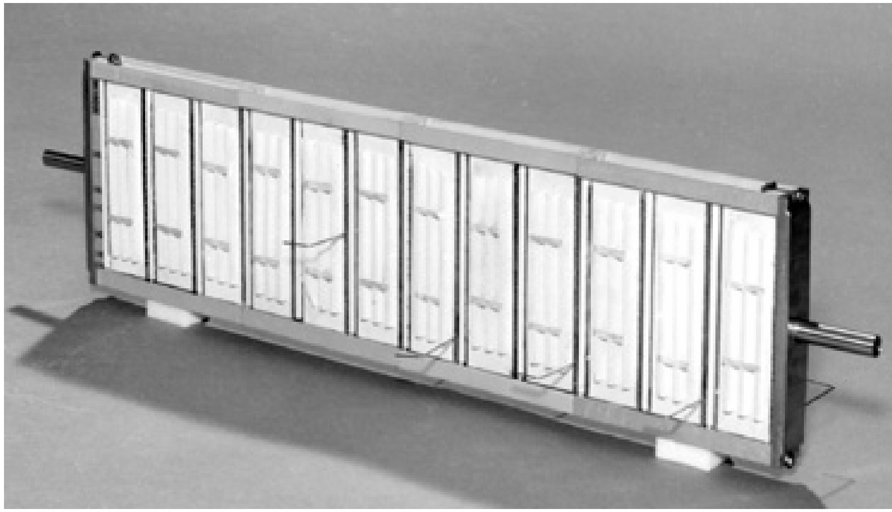



*University of Aviero, Portugal*

- **Overcomes some SOFC limitations**
  - Lower operating temperature allows stainless steel internals
  - No $NO_x$ formation at anode
  - Fuel not diluted by product water
  - Complete ammonia conversion possible
- **Persistent problem: relatively low ionic conductivity at lower T**

# The MCFC and Ammonia

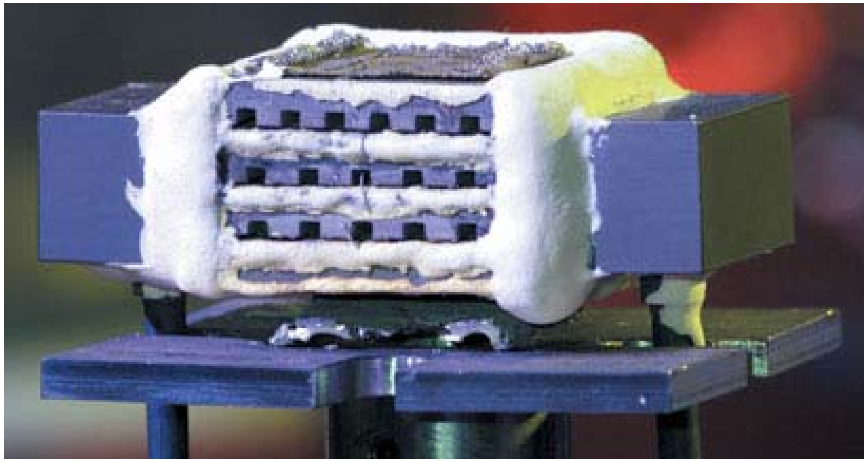
- **MCFC/$NH_3$ is a fair match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Cheaper electrocatalysts
  - Liquid electrolyte, good σ
- **Problems with MCFCs**
  - Electrolyte is very corrosive to FC components
  - Carbon dioxide recycling
  - Ammonia crossover reduces system efficiency significantly



*United States Army*

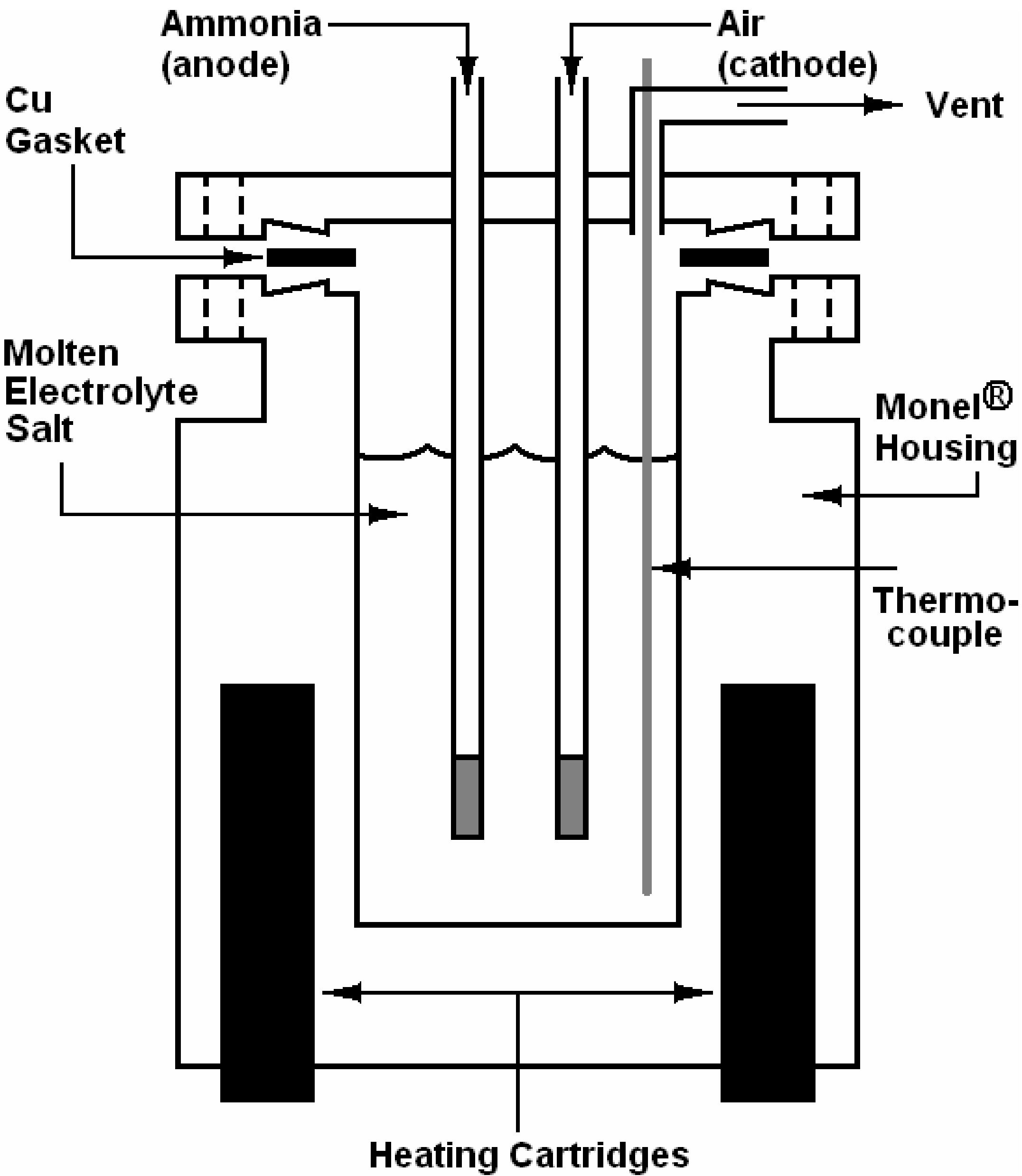
# The SOFC and Ammonia

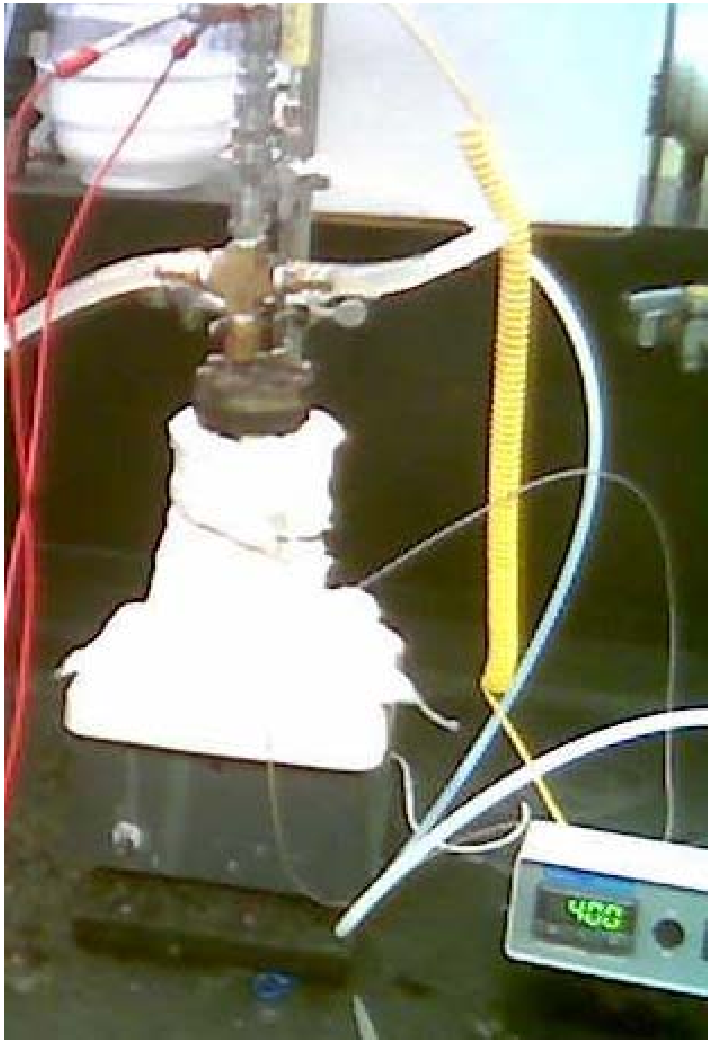
- **SOFC/$NH_3$ is a good match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Ni/cermet electrocatalysts
  - Solid, durable electrolyte
- **Problems with SOFCs**
  - Extreme operating temperature (800-1000°C)
  - $NO_x$ formation at anode
  - Fuel is diluted by product water



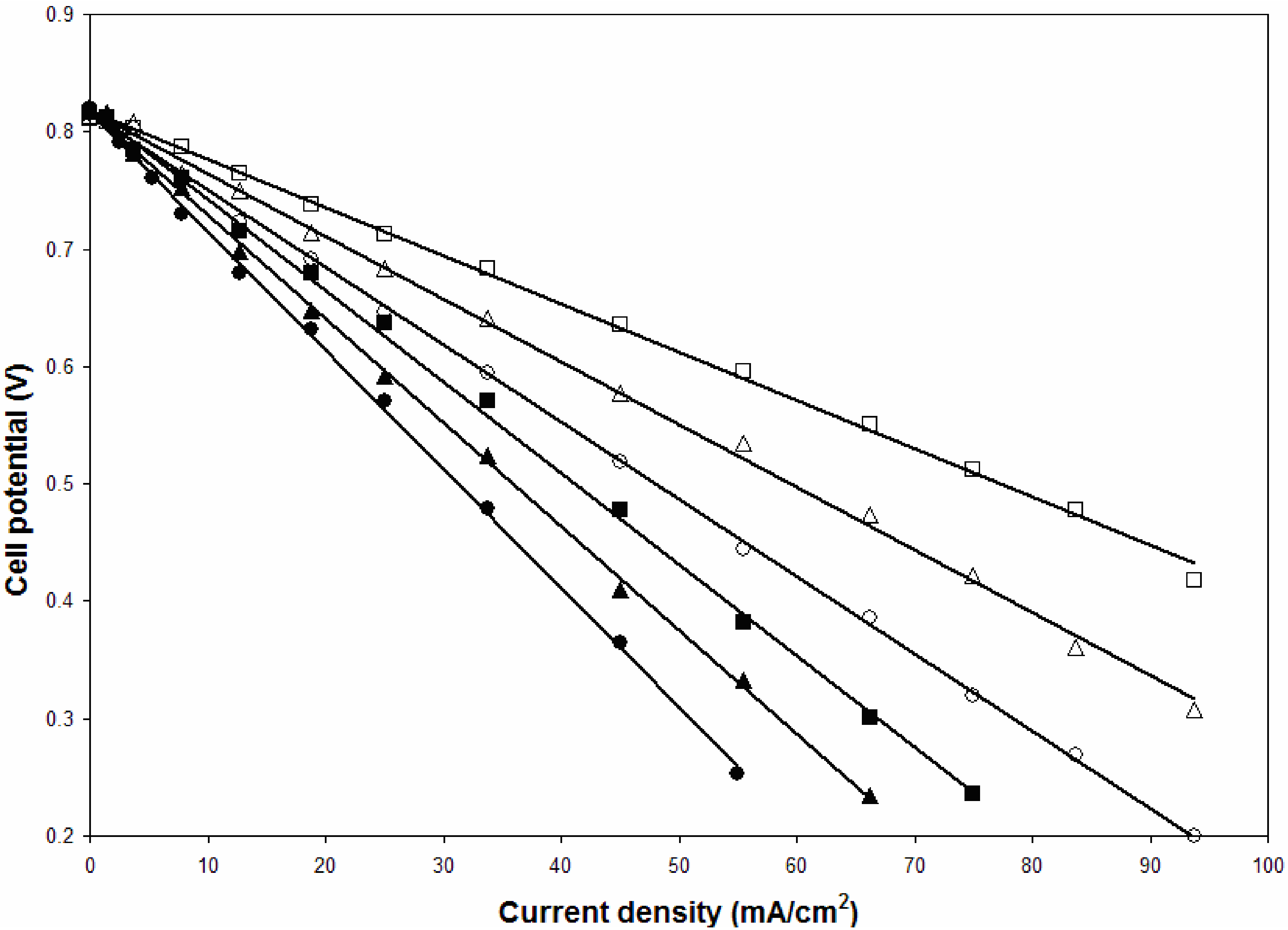
*Lawrence Livermore National Lab*

# High Conductivity, Lower Temp: IT-DAFC



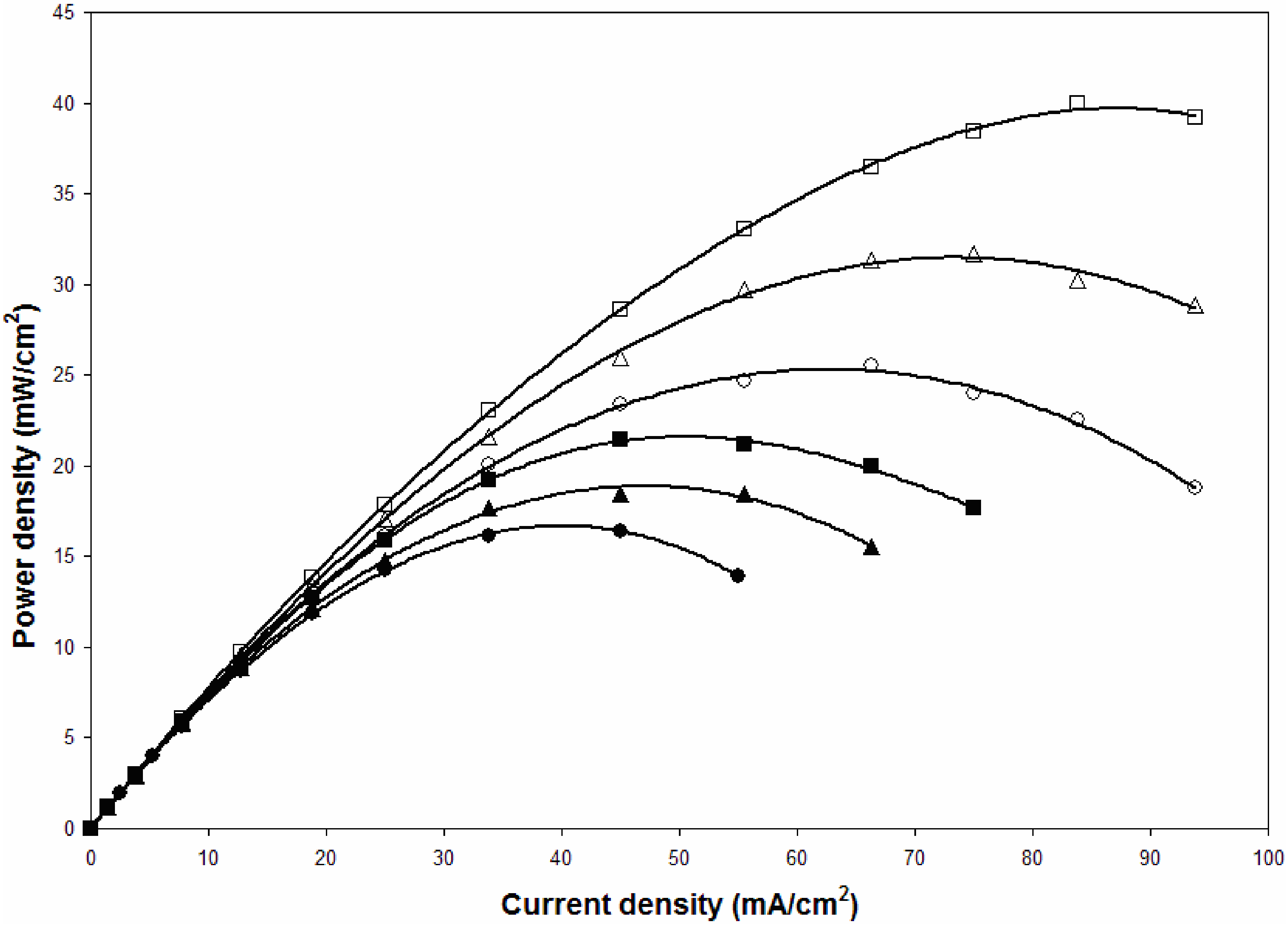



# Ammonia Cell Performance




**Polarization behavior of the direct ammonia fuel cell operating at (●) 200°C, (▲) 250°C, (■) 300°C, (○) 350°C, (Δ) 400°C, and (□) 450°C.**

# Ammonia Cell Performance




**Power production performance of the direct ammonia fuel cell operating at (●) 200°C, (▲) 250°C, (■) 300°C, (○) 350°C, (△) 400°C, and (□) 450°C.**

# Current Efforts

- **Optimization of electrocatalysts**
  - Surface area and porosity
  - Surface chemistry, catalyst promotion
  - Chemical stability within melt
- **Adjustment of molten salt composition**
  - Eutectics vs. pure salts for chosen operating temperature
  - Maximizing ionic conductivity
  - Minimizing chemical incompatibility and volitization
- **Conversion to planar cell geometry**
  - Highest power density of any cell configuration
  - Techniques similar to MCFC construction

# Questions / Discussion