Intermediate Temperature Direct Ammonia Fuel Cells

Jason C. Ganley

Howard University
Department of Chemical Engineering
Washington, DC

Ammonia for Fuel Cells

CH4 103 (1.5 H2)

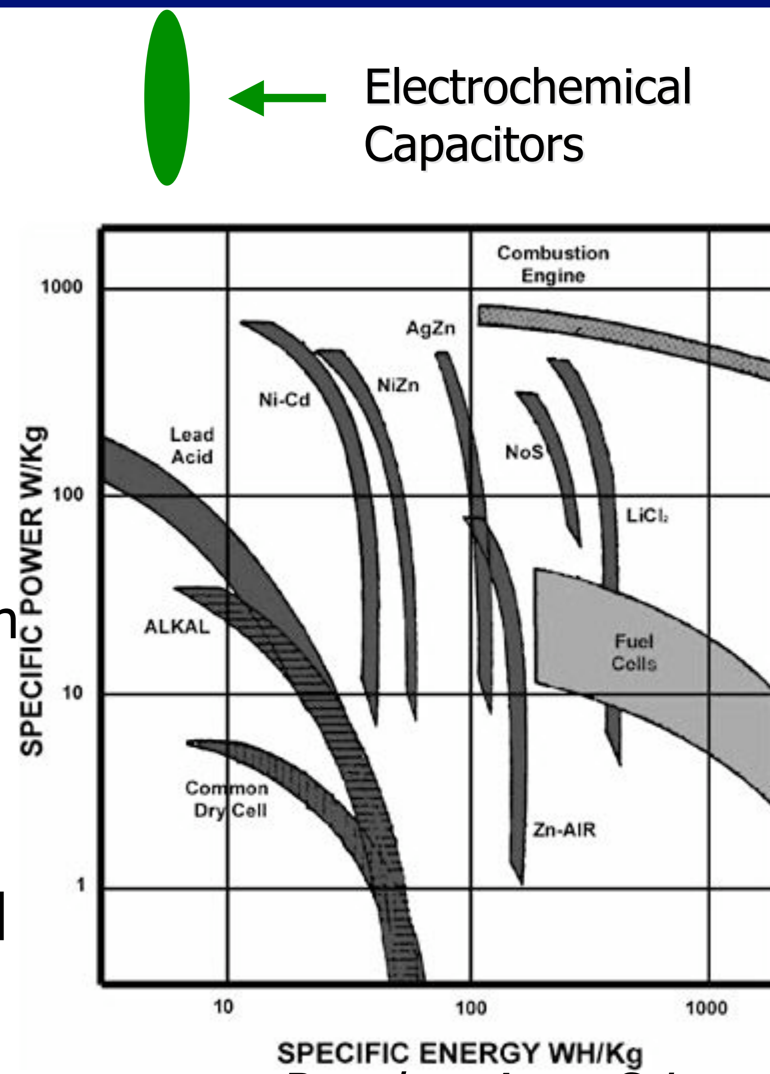
$$2\,NH_3 \longrightarrow 3\,H_2 + N_2 \qquad \Delta H^\circ = 46\ kJ/mol$$

- 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 57 litres 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 (~940 km)

356 kWh nom
150 mi gas

Fuel Cells or ICE?

- **Internal combustion engine**
  - Rated at peak hp
  - My old car: 85 hp Geo Metro
    - Cruising uses only about 10 hp
    - I, however, drive like an old lady
  - Peak hp is only for short periods of time, even in military apps
  - Maximum torque only at certain rpm
- **The electric motor**
  - Rated for continuous power
  - Can provide **at least** 5X rated power intermittently
  - Maximum torque available from a dead stop (0 rpm)



Board on Army Science And Technology (BAST)

Fuel Comparison

Fuel	Base MJ/liter	Reformed MJ/liter*
H_2 (5000 psia)	4.0	4.0
H_2 (liq.)	9.9	9.9
NH_3 (liq.)	15.3	13.6
Methanol	17.9	10.2
Ethanol	23.4	9.1
Propane (liq.)	29.4	8.6
Gasoline	36.2	9.2
JP-8	40.5	9.7

* **Includes heat and water volume required for steam reforming**

Operating Temperature: A Key Characteristic

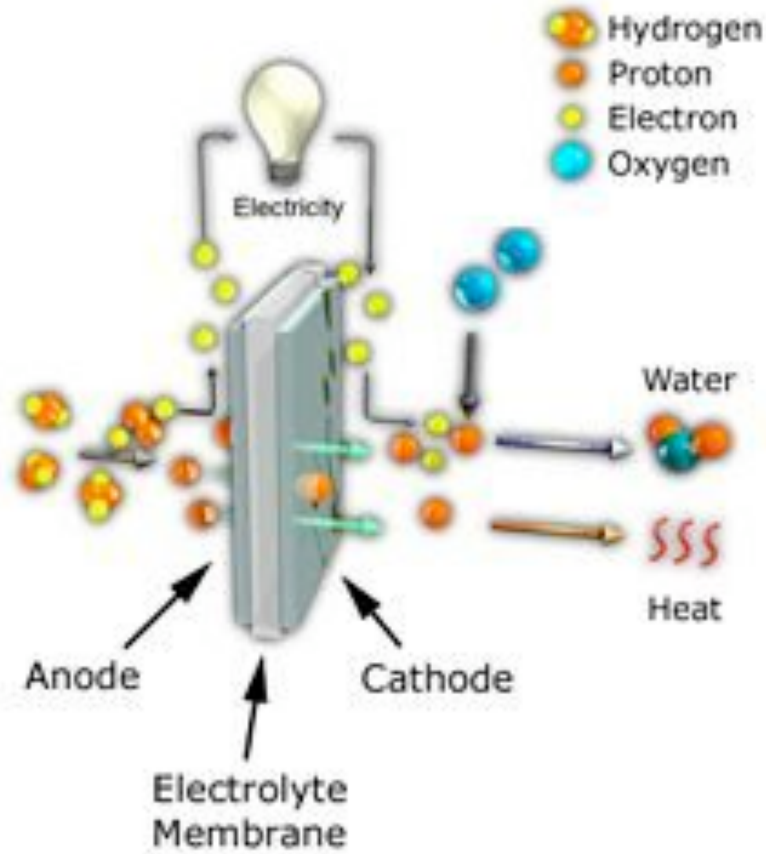
- **Low Temperature Fuel Cell Advantages**
  - Quick start-up to operating temperature (~100°C)
  - Wide range of cell construction materials
- **High Temperature Fuel Cell Advantages**
  - Fuel flexibility via internal fuel reforming
  - Inexpensive, base metal electrocatalysts
  - Easier heat recovery 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) [150°C, OH^-]
- Phosphoric Acid Fuel Cells (PAFC) [220°C, H^+]
- Protonic Ceramic Fuel Cell (PCFC) [550°C, H^+] [Intermediate Temp Fuel Cell, 300-500°C]
- Protonic Ceramic Fuel Cells (PCFC) [550°C, H^+] Molten Carbonate Fuel Cells (MCFC)
- Molten Carbonate Fuel Cells (MCFC) [650°C, CO_3^{2-}]
- Solid Oxide Fuel Cells (SOFC) [900°C, O^{2-}] [650°C, CO_3^{2-}]
- Solid Oxide Fuel Cells (SOFC) [900°C, O^{2-}]

PAFCs/PEMFCs and Ammonia

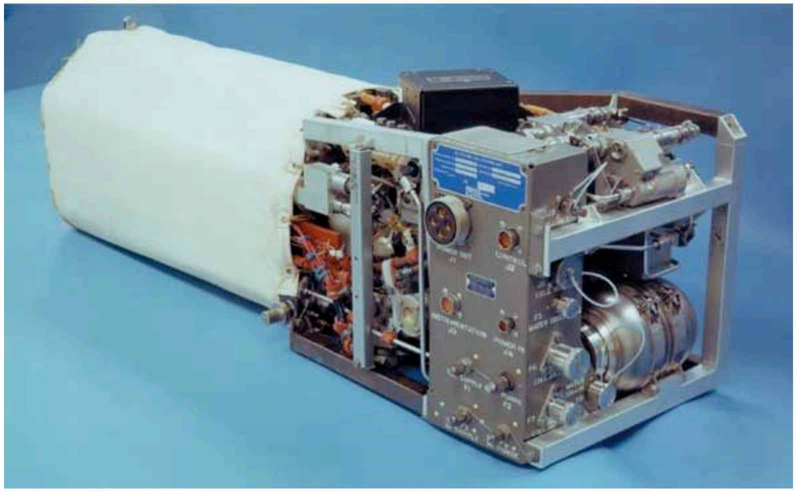
- **External NH_3 reforming required**
  - Trace NH_3 poisons acid membrane
  - Even well-reformed fuel must be scrubbed
- **Temperature and humidity issues**
  - Above 100°C, membrane dries out, loses conductivity
  - Inefficient heat recovery
  - Precious metal electrocatalysts required



Plug Power Inc.

Alkaline FCs and Ammonia

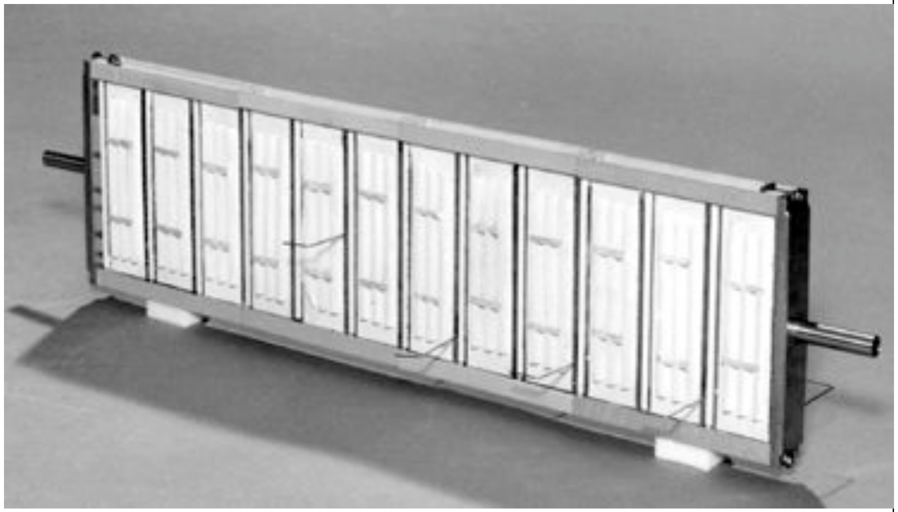
- **AFCs are tolerant of residual NH_3**
  - Still must crack NH_3 externally
  - Precious metal catalysts
- **Lifetime issues**
  - Corrosive electrolyte
  - Intolerant of CO_2
    - Formation of carbonate precipitates
    - Fuel and air streams must be purified
  - Expensive immobilization matrix for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



United Technologies

The MCFC and Ammonia

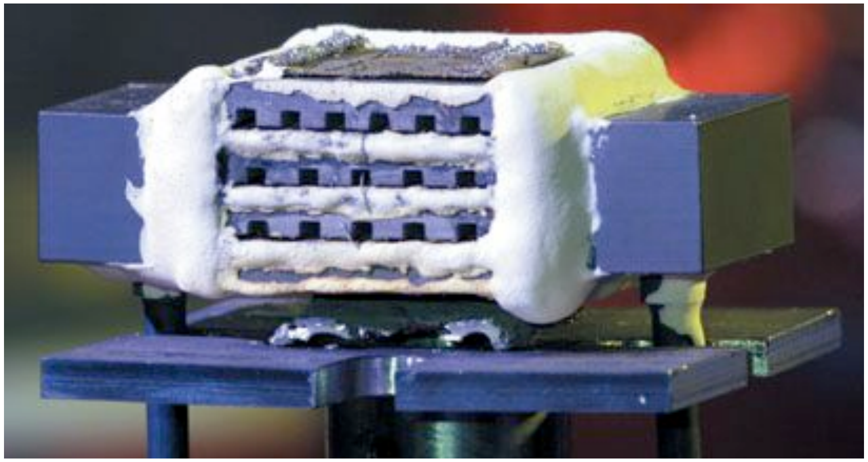
- **MCFC/NH_3 is a fair match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Cheaper electrocatalysts
  - Liquid electrolyte, good σ
- **Problems with MCFCs**
  - Electrolyte is very corrosive to FC components
  - Carbon dioxide recycling
  - Not suited to intermittent use
  - Ammonia crossover reduces system efficiency significantly



United States Army

The SOFC and Ammonia

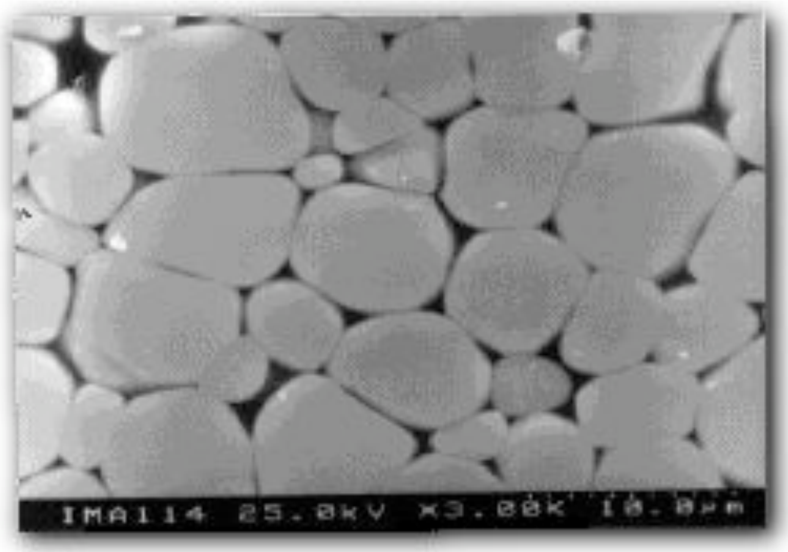
- **SOFC/NH_3 is a very good match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Ni/cermet electrocatalysts
  - Solid, durable electrolyte
- **Problems with SOFCs**
  - Extreme operating temperature not conducive to mobile applications
  - NO_x formation at anode
  - Fuel is diluted by product water



Lawrence Livermore National Lab

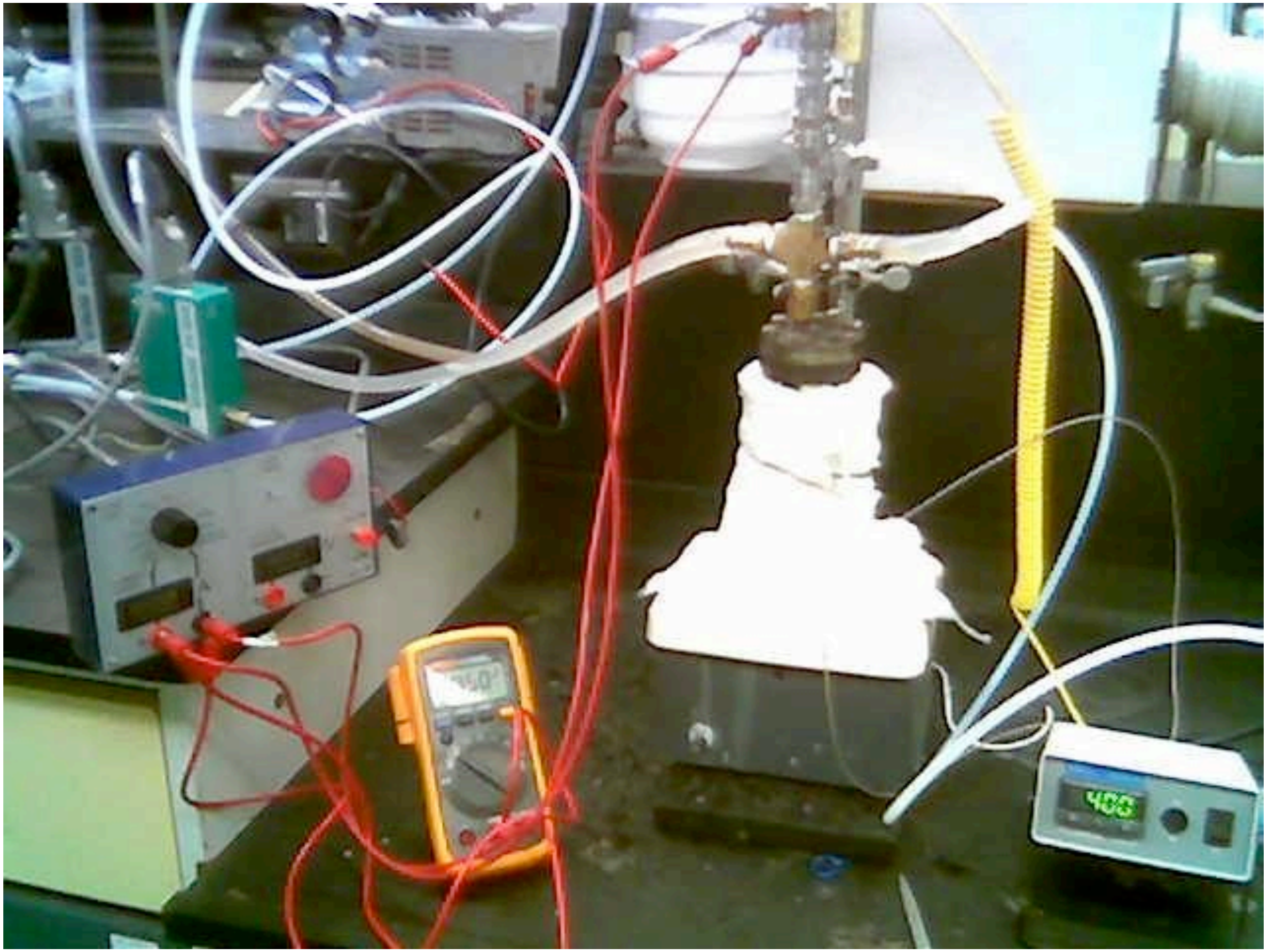
The PCFC and Ammonia

- **PCFC/NH_3 is an excellent match**
  - Direct-ammonia capable
  - Efficient heat recovery
  - Ni/cermet electrocatalysts
  - Solid, durable electrolyte
- **Overcomes 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

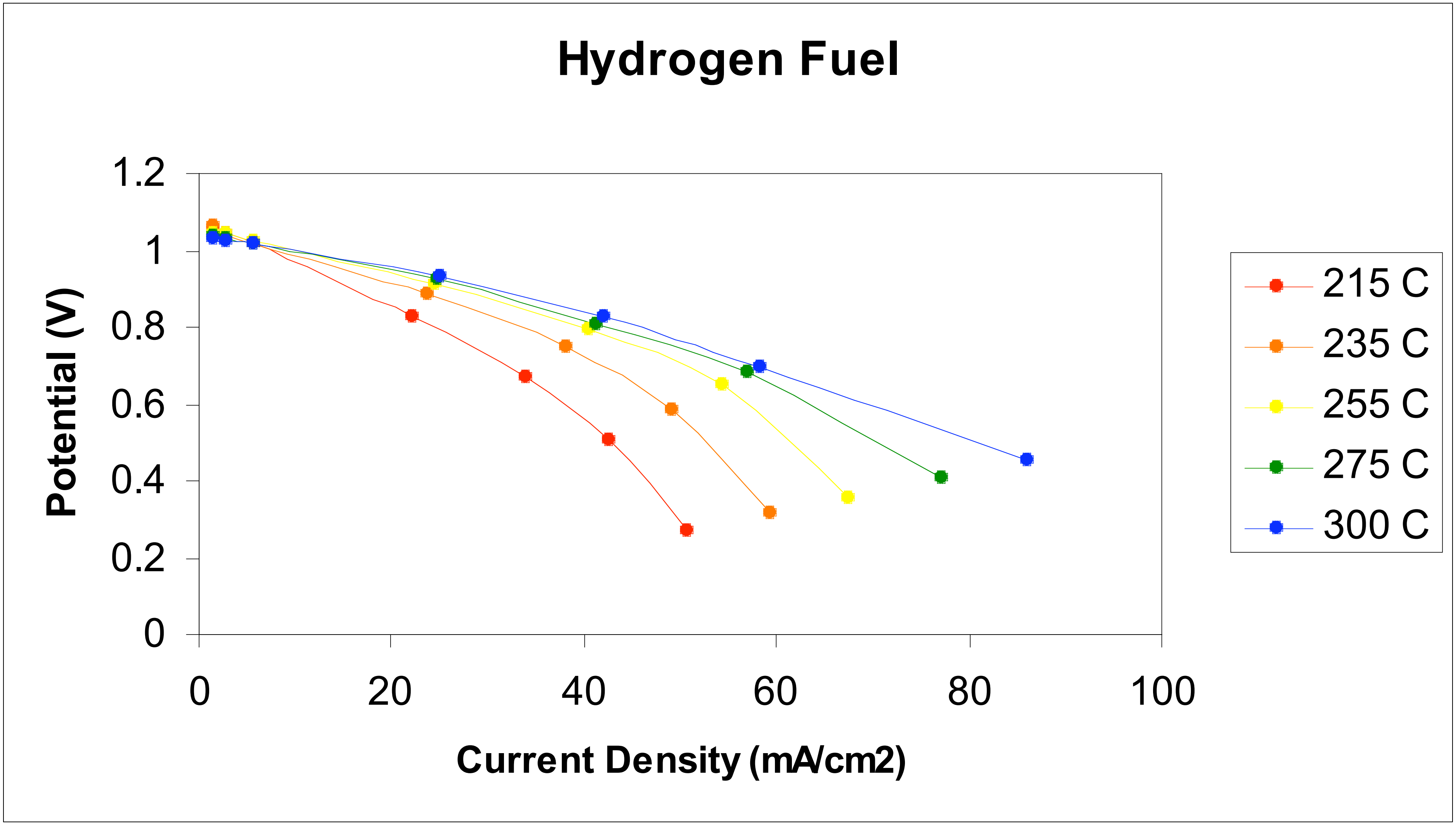


University of Aviero, Portugal

Filling the Temperature Gap: Intermediate Temperature DAFC



Hydrogen Cell Performance



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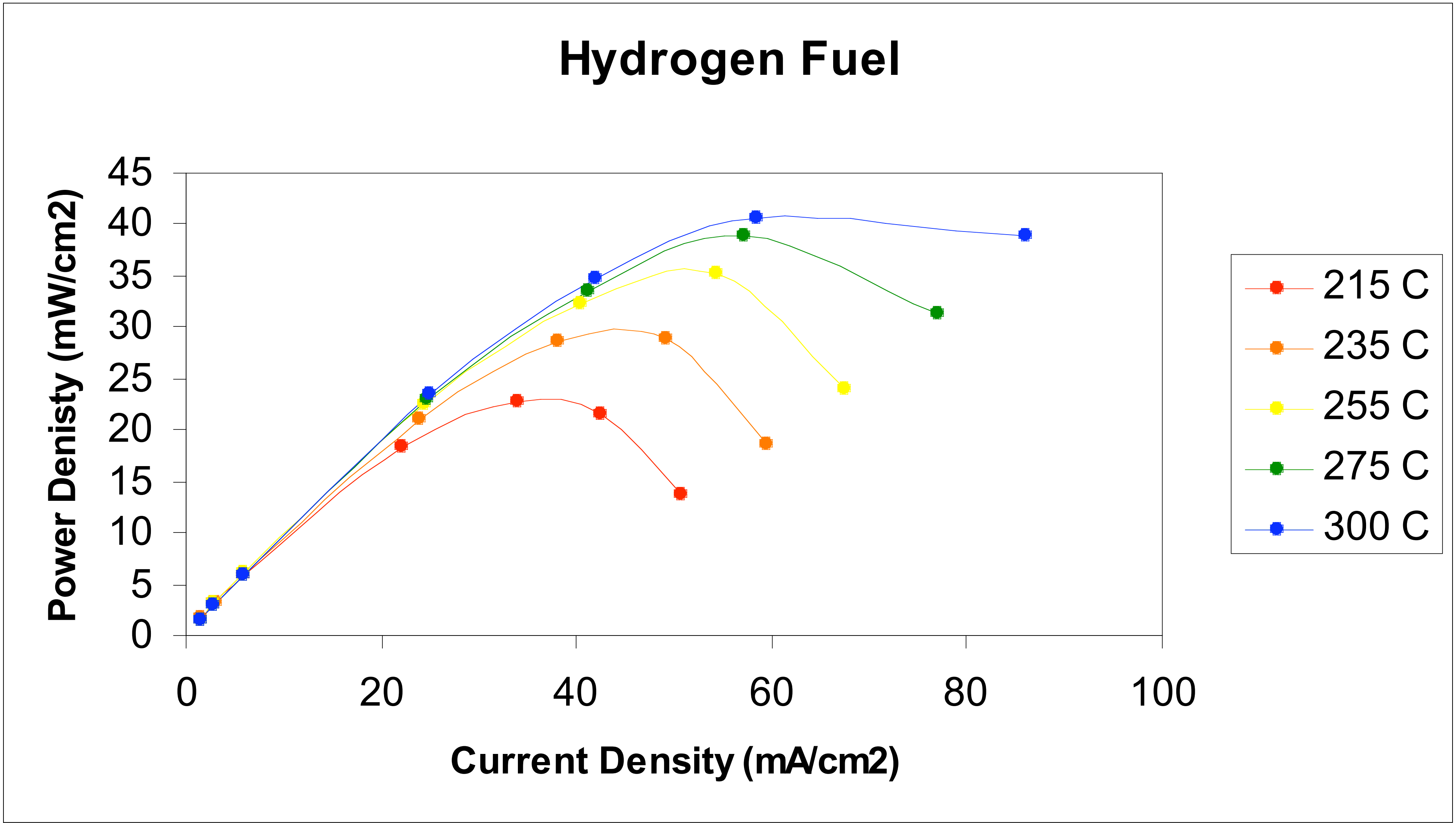
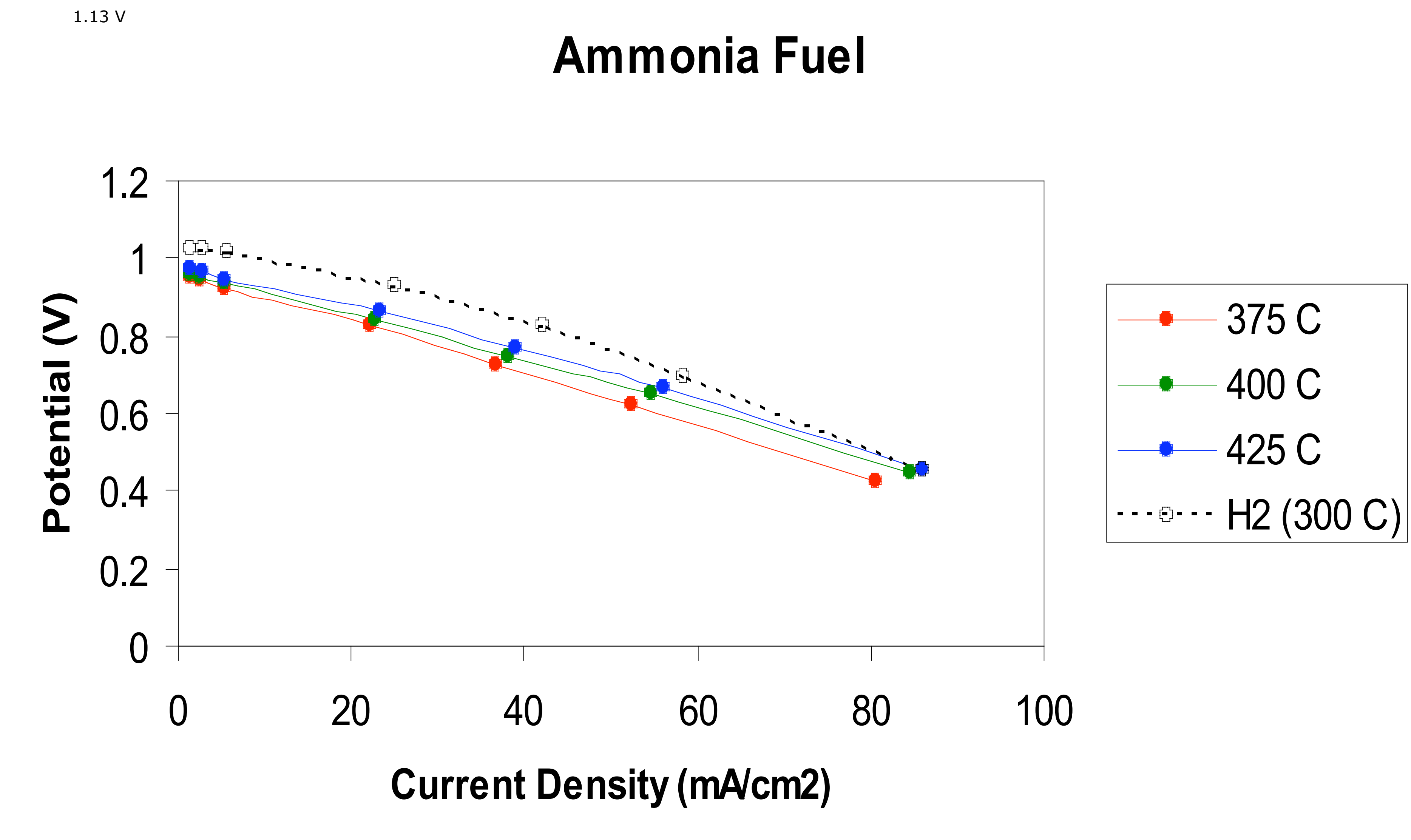


Ammonia Cell Performance



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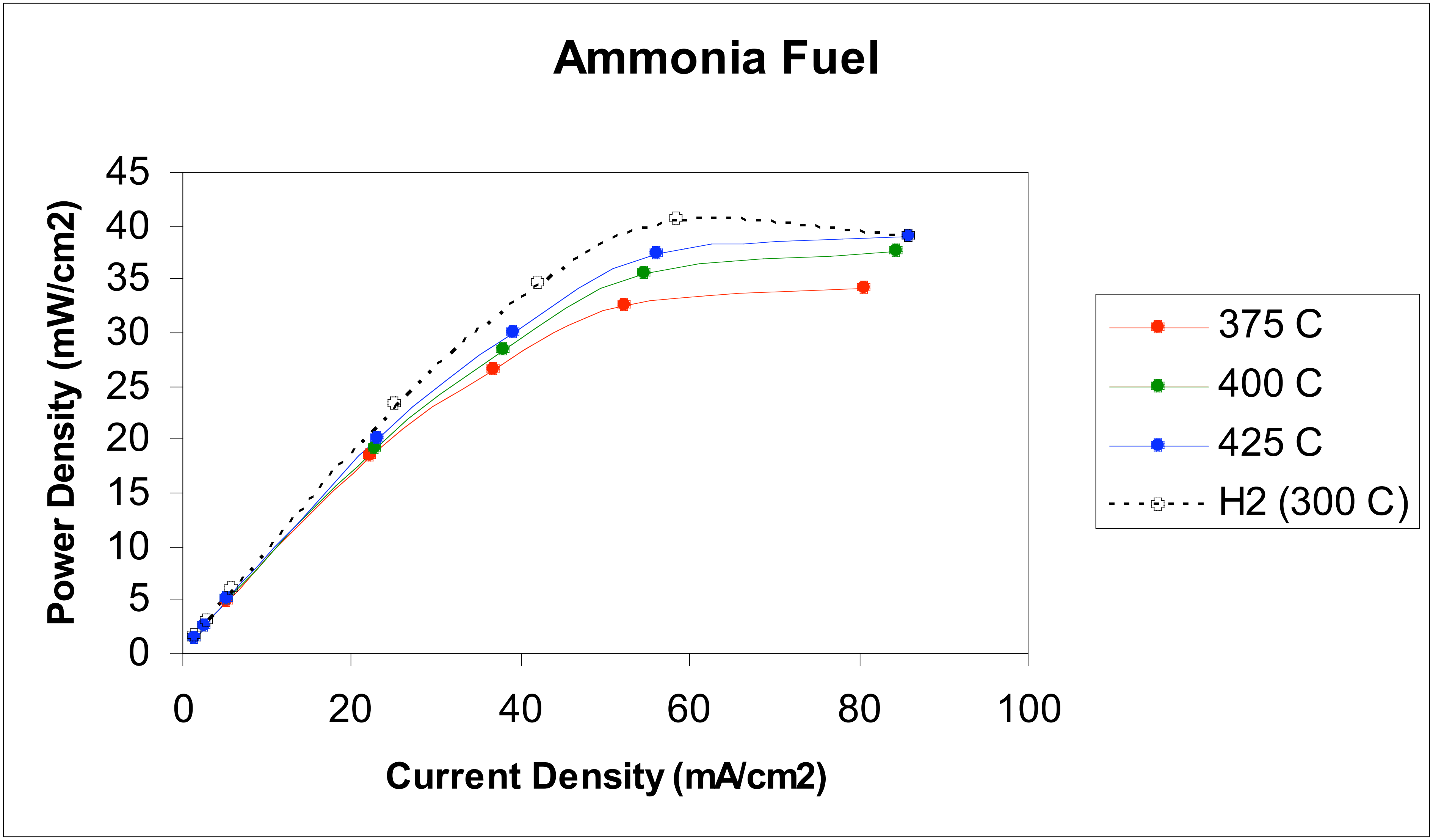
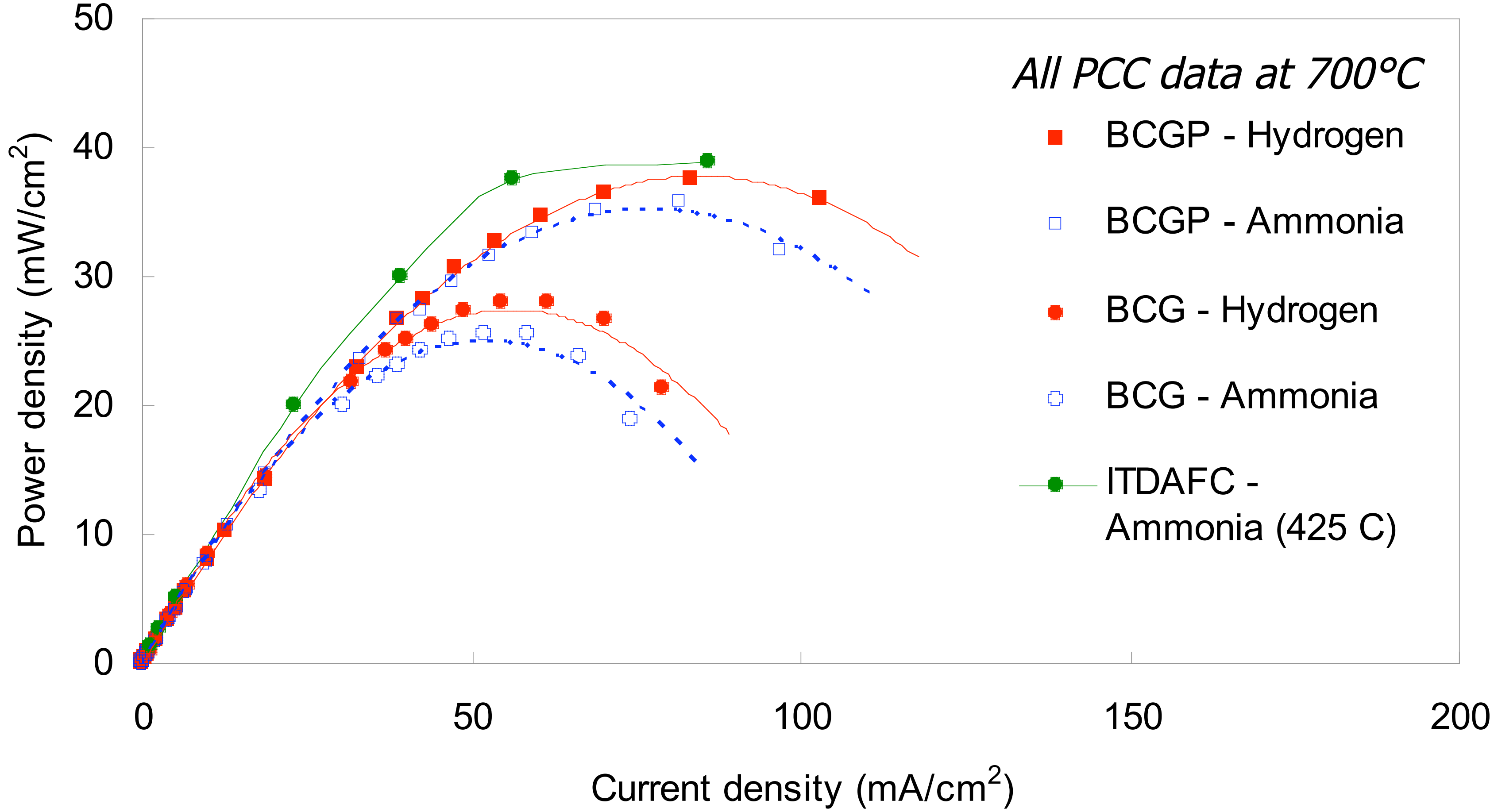


Comparison with NH_3 PCC



Modified from A. McFarlan, NRC

What's the plan? Build a Car, of Course

- **A med-temperature fuel cell main power plant: 90 kW**
  - Ammonia fuel
    - Non-explosive, energy dense
    - Reactive-walled fuel tank
  - 60 kW electric motor drive
    - Capable of delivering 300 kW bursts
    - Torque controlled electronically
    - Out-accelerates comparable ICE

The Holbrookmobile

- **Ultracapacitor bank**
  - Regenerative braking
  - Charges during cruising and "idling"
  - Power dump to motor for bursts

EV-1 Conversion

- **General Motors donation to Howard University**
  - All technical manuals and specifications available
  - No battery pack
- **Goal: convert EV-1 to a hybrid fuel cell vehicle**
  - Challenges: FC design, installation, and control
  - Creation of a new project for undergraduate and graduate hands-on education
  - Will involve multiple disciplines

(General Motors)

Questions/Discussion

Jason C. Ganley
Howard University
Department of Chemical Engineering
2300 6th Street, NW
Washington, DC 20059
(202) 806-4796
jganley@howard.edu