# Flexible Tubular Alkaline Fuel Cells

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# Prelude to Tubular Alkaline Fuel Cells

- Flameless Ration Heaters (FRH) are used to heat Meals, Ready to Eat (MRE) and Unitized Group Ration (UGR)
  - Upon activating with water, they release heat, steam, and hydrogen
- Need to
  - Capture or react the hydrogen to avoid explosive limits from being reached
  - Mitigate actual and perceived safety concerns with hydrogen presence
- Challenges:
  - Cost needs to be comparable with $10/UGR heater
  - Must destroy a lot of hydrogen (11.3 $Ft^3$) in a short time (30-45 min)
  - Must be lightweight and compact
  - Readily integratable with UGR heaters

The flameless ration heaters work by reacting water with Mg to release a mixture of steam and hydrogen gas

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# UGR Activation


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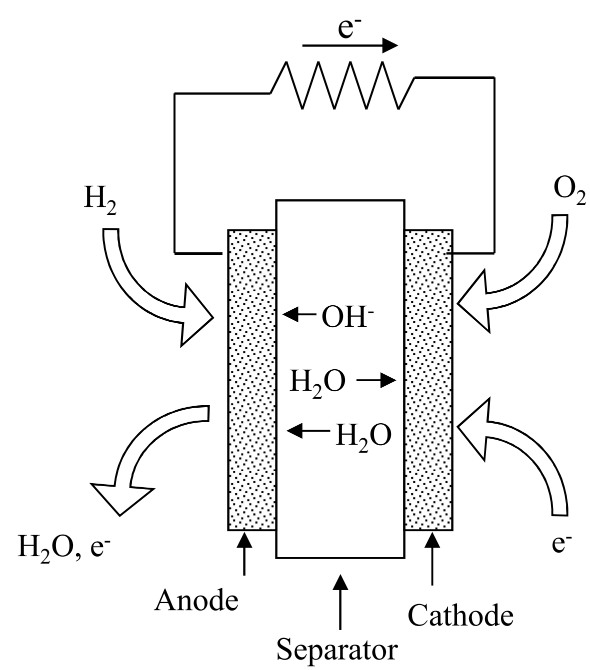
# Alkaline Fuel Cell Approach Minimizes Cost

- Presently used on-board the Space Shuttle
- Extensions to terrestrial applications difficult
  - Electrolyte leakage, corrosion, and carbonate buildup limit lifetime and increase cost
- However, for the UGR application
  - Longevity not required, only 30 min
  - Electrolyte can be stored dry until activated with water
  - Negligible $CO_2$ adsorption in 30 min
  - Inexpensive materials may be used for the single use application

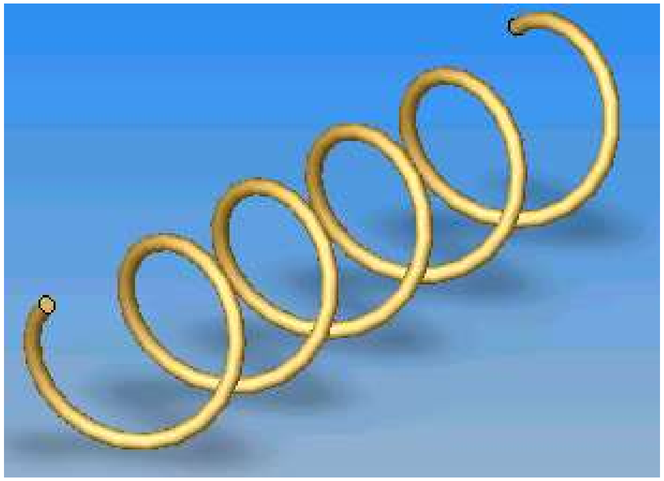



Anode: $H_2 + 2OH^- \rightarrow 2H_2O + 2e^-$

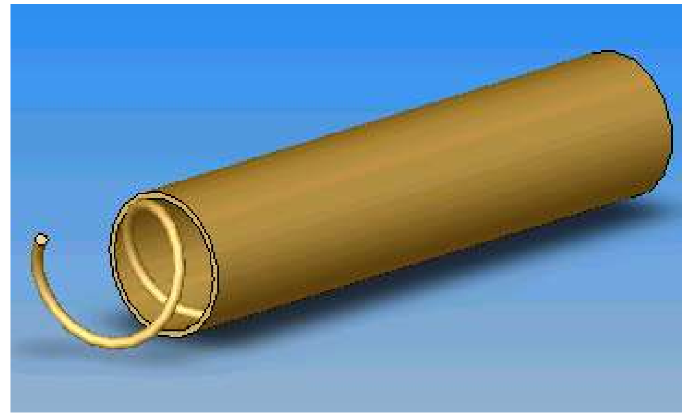
Cathode: $O_2 + 2H_2O + 4e^- \rightarrow 4OH^-$

Total: $H_2 + \frac{1}{2}O_2 \rightarrow H_2O$

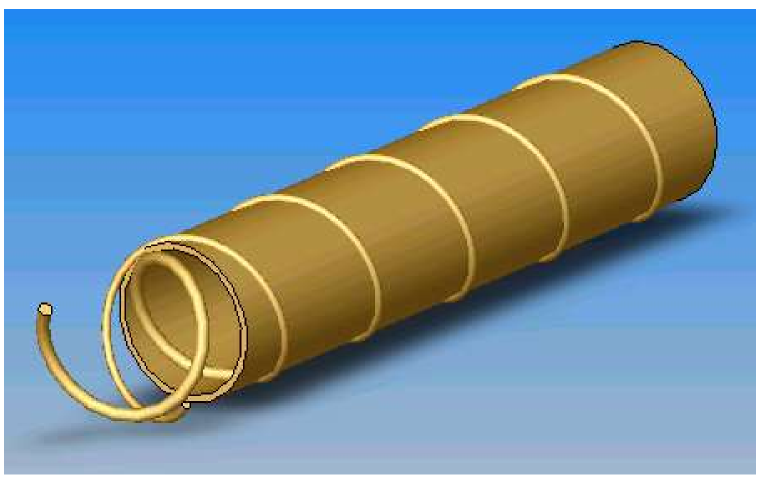
# FCord™: A Tubular Alkaline Fuel Cell That Produces Heat Along the Cell



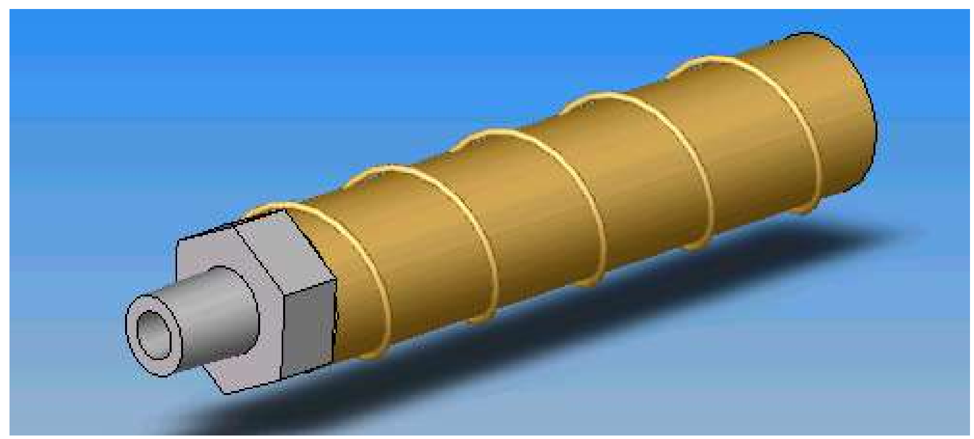
1. Coil Anode Ni Wire



2. Wrap With Separator and KOH



3. Wrap Cathode Ni:Cr Wire



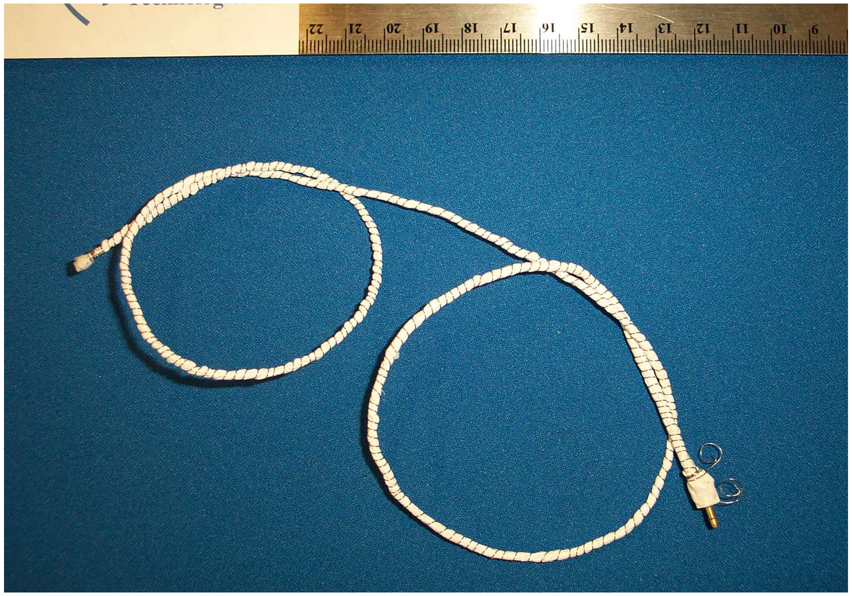
4. Insert H2 Fitting and
Connect Electrodes

# Design for Manufacturability

- Fuel cell development philosophy focused on being able to manufacture the tubular alkaline fuel cell (FCord)
- Low cost, textile manufacturing process envisioned for the tubular AFC
- Example picture of multiple fiberglass strands being wound around a mandrel – our model for the tubular AFC!

# Compact and Flexible Tubular Alkaline Fuel Cells

- Some technical challenges
  - Air breathing cathode
  - Flexible and conductive electrodes and current collectors
  - No radial hydrogen leakage
  - Low cost components
    - Porous Ni, $MnO_2$, fiberglass



Patent Pending

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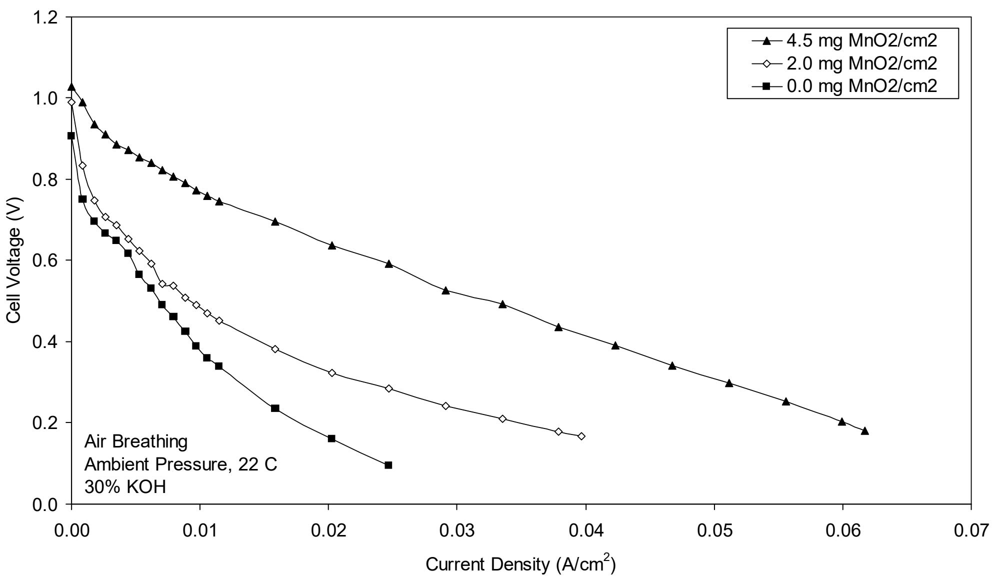
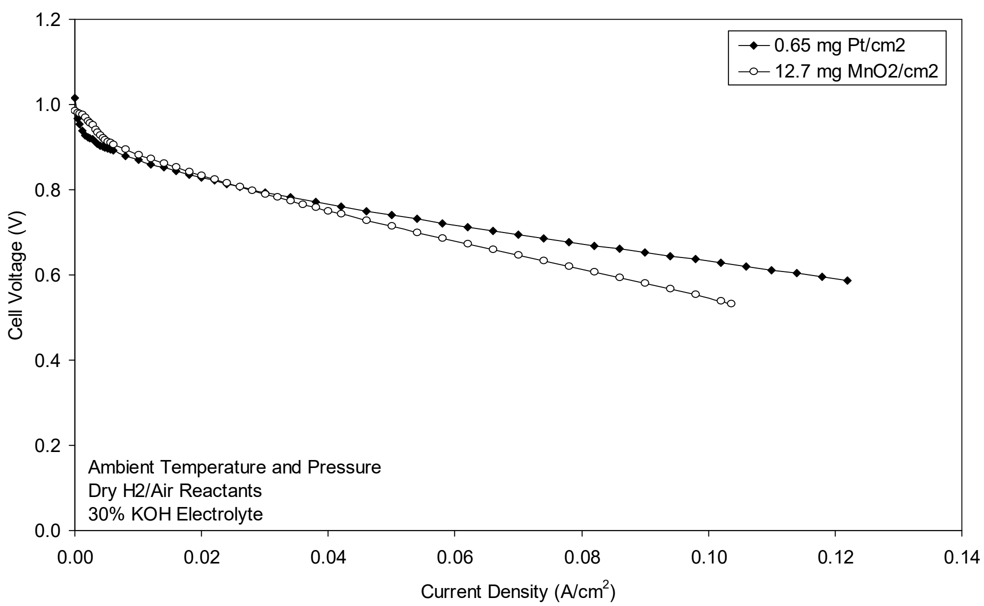
# Catalyst Development

- Requirements
  - Porous nickel (Raney Ni™) based anode catalyst for low cost
  - $MnO_2$ based cathode catalyst for low cost
  - Paintable or sprayable inks onto nickel mesh or wire
  - Electrode must be able to flex without catalyst delaminating
  - Target electrochemical performance point of 0.5 A/cm$^2$ at 0.1 V
- Anode
  - Operation with dry to saturated hydrogen (85-95 C) on the interior of the tubular fuel cell
- Cathode
  - Operation with ambient air diffusion to the exterior surface of the tubular fuel cell

# Air Breathing $MnO_2$ Based Cathodes Show Competitive Performance to Platinum




- Alkaline fuel cell performance at ambient pressure and temperature
- Ambient air breathing cathodes
- Higher $MnO_2$ loadings increase alkaline fuel cell performance
- Competitive performance to platinum based cathode

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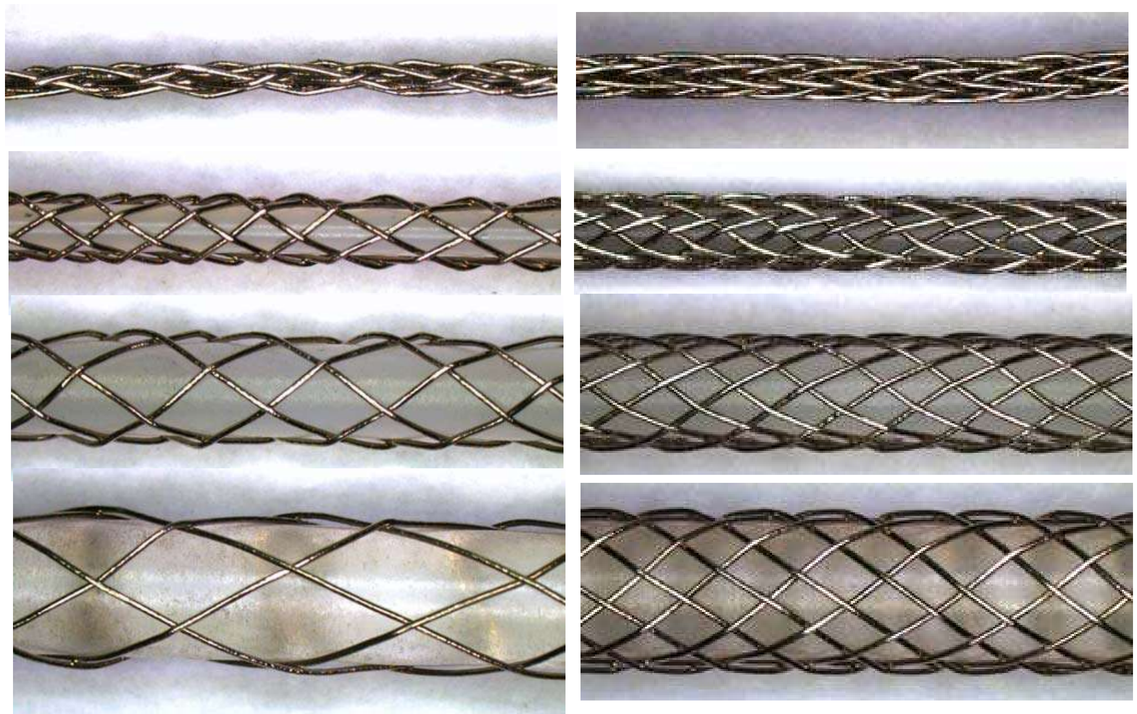
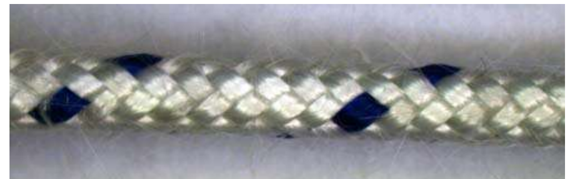
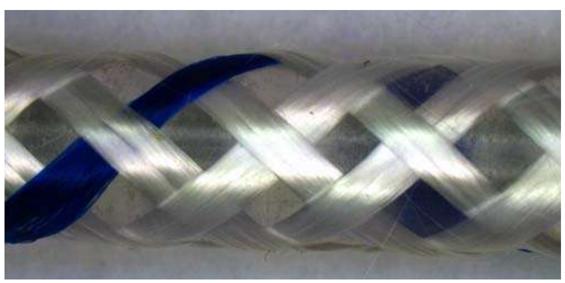
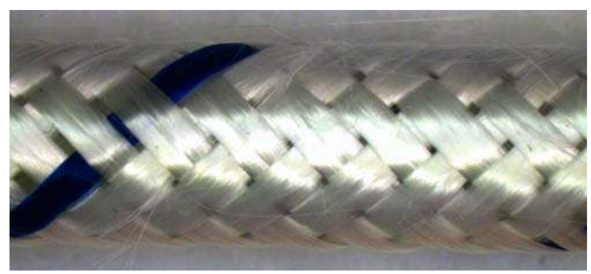
# Braided Current Collector Technology Developed for Variable Sized Mandrels and Strand Count

| | 8-Strand | 16-Strand |
|---|---|---|
| No mandrel | R = 0.016 ohm | R = 0.010 ohm |
| 1/16” mandrel | R = 0.022 ohm | R = 0.012 ohm |
| 1/8” mandrel | R = 0.032 ohm | R = 0.012 ohm |
| 3/16” mandrel | R = 0.029 ohm | R = 0.013 ohm |

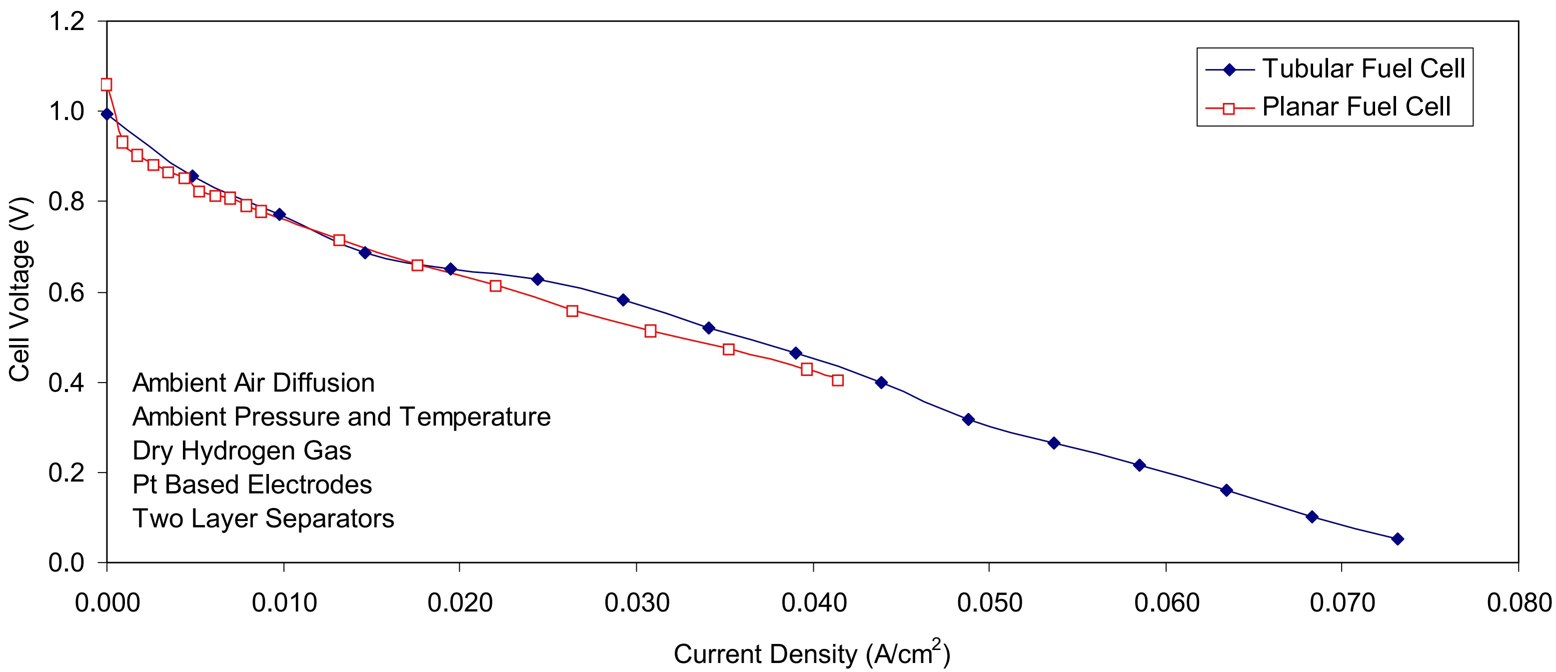


Braided 10 mil Ni wire gives acceptable voltage drop over 10 cm length

# Braided Fiberglass Separator Developed for Variable Sized Mandrels and Strand Count

| | 8-Strand | 16-Strand |
|---|---|---|
| 1/16" mandrel |  |  |
| 1/8" mandrel |  |  |
| 3/16" mandrel |  |  |
| 1/4" mandrel |  |  |

# Double Layer Braided Separator in Tubular Fuel Cells Show Comparable Performance to Planar Cells

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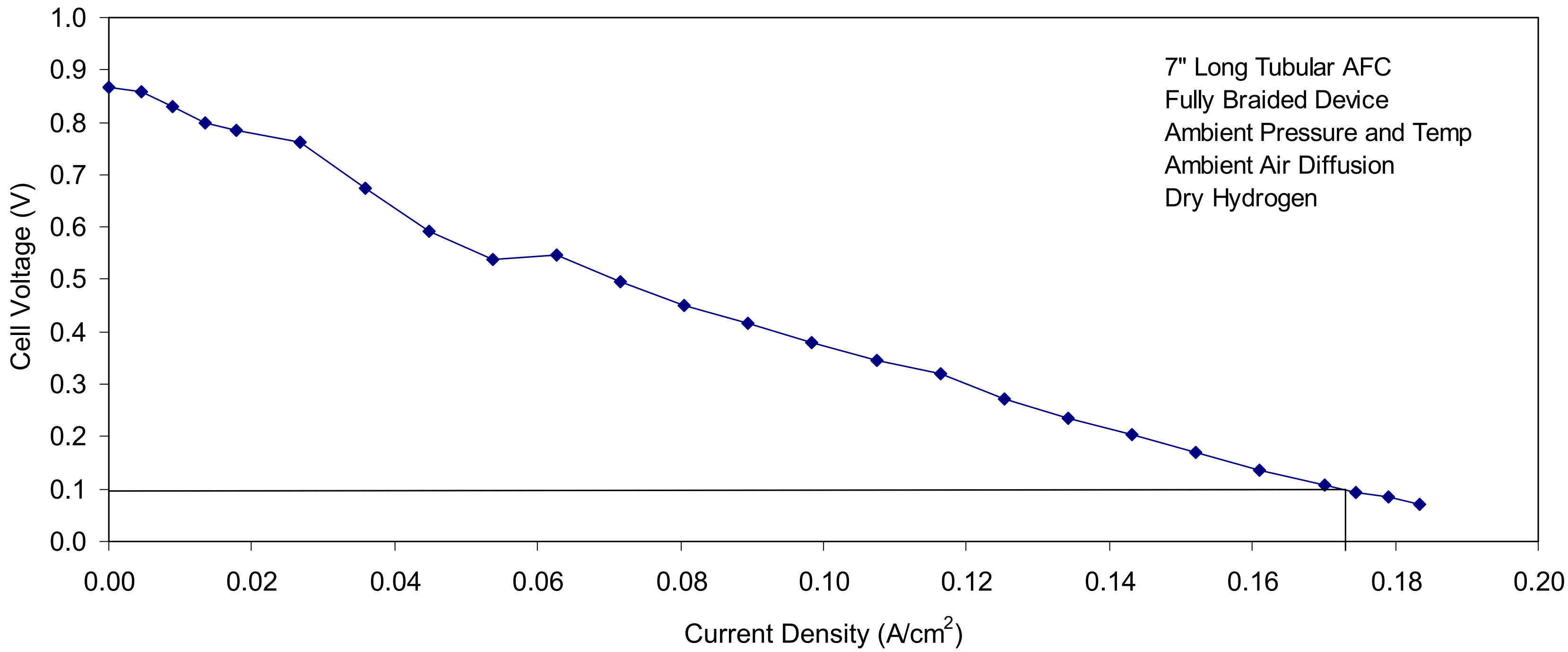
# 7” Long Fully Braided Tubular AFC Shows 0.17 A/cm$^2$ at 0.1 V

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# Material Costs for Measured and Improved Performance

| Measured Data to Date | |
|---|---|
| **Quantity** | **Value** |
| H2 mol produced | 10.18 |
| Rate (H2 mol/min) | 0.226 |
| Current (amps) | 727.4 |
| Amps/tray (4) | 181.8 |
| Cur Den (A/cm2) | 0.10 |
| @ voltage | 0.20 |
| Area (cm2)/tray | 1818.4 |
| Tube Diameter (in) | 0.125 |
| Tube Length (cm)/tray | 1823.0 |
| Tube Length (ft)/tray | 59.8 |
| Length/RUSHM (cm) | 7292.1 |
| Area/RUSHM (cm2) | 7273.6 |

| Component | Material Cost ($) |
|---|---|
| Anode Cur. Col. | 54.81 |
| Anode Catalyst | 43.71 |
| Separator | 4.05 |
| Cathode Catalyst | 2.11 |
| Cathode Cur. Col. | 78.38 |
| Total Cost/RUSHM | 183.06 |

| Measured Data to Date | |
|---|---|
| **Quantity** | **Value** |
| H2 mol produced | 10.18 |
| Rate (H2 mol/min) | 0.226 |
| Current (amps) | 727.4 |
| Amps/tray (4) | 181.8 |
| Cur Den (A/cm2) | 0.50 |
| @ voltage | 0.30 |
| Area (cm2)/tray | 363.7 |
| Tube Diameter (in) | 0.125 |
| Tube Length (cm)/tray | 364.6 |
| Tube Length (ft)/tray | 12.0 |
| Length/RUSHM (cm) | 1458.4 |
| Area/RUSHM (cm2) | 1454.7 |

| Component | Material Cost ($) |
|---|---|
| Anode Cur. Col. | 10.96 |
| Anode Catalyst | 8.74 |
| Separator | 0.81 |
| Cathode Catalyst | 0.42 |
| Cathode Cur. Col. | 15.68 |
| Total Cost/RUSHM | 36.61 |

| Expected Performance Improvements | |
|---|---|
| **Quantity** | **Value** |
| H2 mol produced | 10.18 |
| Rate (H2 mol/min) | 0.226 |
| Current (amps) | 727.4 |
| Amps/tray (4) | 181.8 |
| Cur Den (A/cm2) | 1.00 |
| @ voltage | 0.30 |
| Area (cm2)/tray | 181.8 |
| Tube Diameter (in) | 0.125 |
| Tube Length (cm)/tray | 182.3 |
| Tube Length (ft)/tray | 6.0 |
| Length/RUSHM (cm) | 729.2 |
| Area/RUSHM (cm2) | 727.4 |

| Component | Material Cost ($) |
|---|---|
| Anode Cur. Col. | 5.48 |
| Anode Catalyst | 4.37 |
| Separator | 0.41 |
| Cathode Catalyst | 0.21 |
| Cathode Cur. Col. | 7.84 |
| Total Cost/RUSHM | 18.31 |

About $37 for 200 Watts

# Tubular Alkaline Fuel Cell Summary

- Paintable electrodes developed for anode and cathode based on low cost materials
  - Measured performance of 0.1 to 0.2 A/cm$^2$ at 0.1 V with near term targets of 0.5 A/cm$^2$ at 0.1 V
  - Current collectors developed based on braided wire with low electrical resistance that are flexible
- Separator developed based on double layer braiding
  - Impermeable to hydrogen gas when wetted
  - Shows similar ionic conductivity when re-wetted to 30% KOH
- FRH integration examined to identify permissable pressures and temperatures in the tubular AFC
  - Tubular cell size needs to keep FRH back-pressure less than 2.0 psig at 100 C
  - Rapid temperature rise in tubular AFC on the order of seconds once FRH activated
- Tubular fuel cell showing performance at 0.2 A/cm$^2$ at 0.1 V
  - Reproducible manufacturing process developed for tubular cell
- Economic cost assessment of materials conducted
  - Present cost of $183-$37/UGR with today's measured performance

# Acknowledgment


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