RIL-355

Electrochemical Oxygen Separation from Aircraft Fuel Tank Ullage

Daniel R. Carr and Michael C. Kimble
Reactive Innovations, LLC

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www.reactive-innovations.com 2 Park Drive, Unit 4 Westford, MA 01886 (978) 692-4664

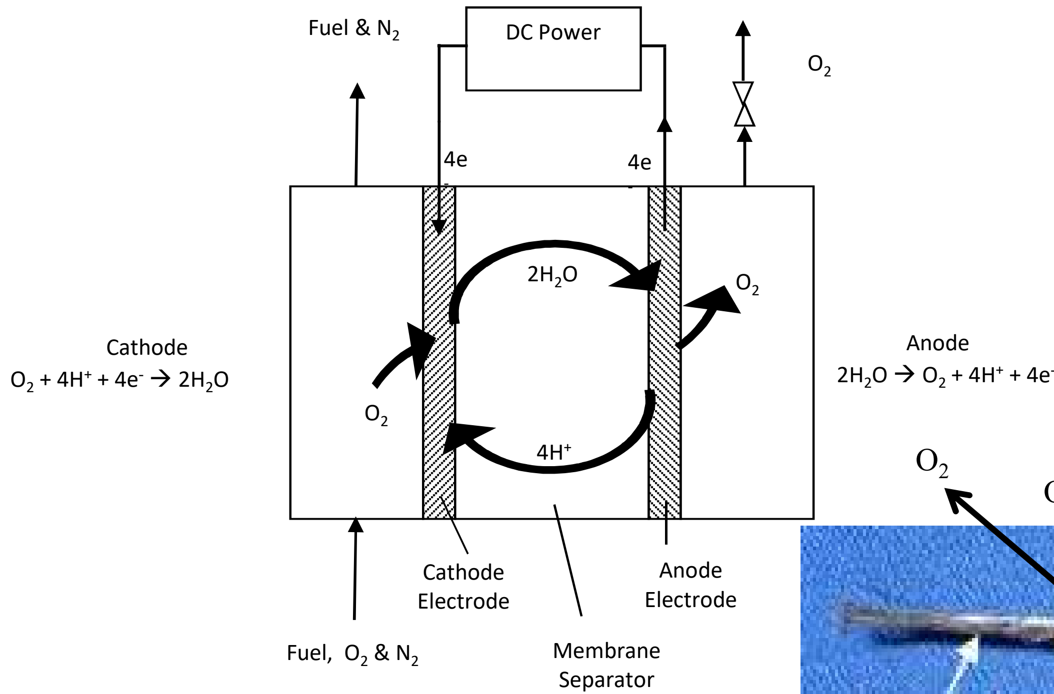
Importance of Separating Oxygen from Aircraft Fuel Tank Ullage

- During flight operations, aircraft fuel tanks contain oxygen rich fuel vapor that can combust
- This leads to explosion and fires as a result of
  - Sloshing fuel, lightning, static discharge, and electrical shorts
- This was demonstrated on July 17, 1996
  - A Boeing 747 exploded in mid-air leaving the East coast
- FAA and military flight operations have shown that reducing the O_2 content to less than 9% eliminates the possibility of combustion
- Inerting systems fill the ullage space with an inert gas
  - Stored suppressants such as explosion suppression foam, nitrogen or halon
  - OBIGGS (On-Board Inert Gas Generating System) generating inert gas via compressing air through a separation bed
- However, these systems are often heavy, costly, and can create logistical resupply challenges for military operations

Fuel Inerting for the V-22 Aircraft

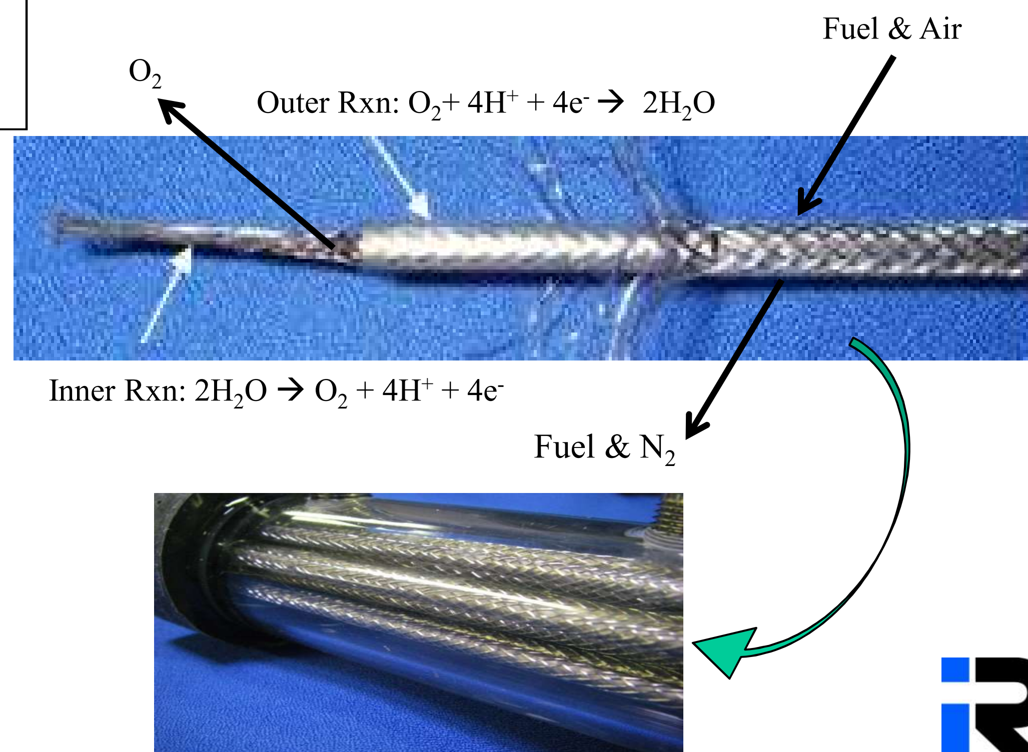
- For military aircraft such as the V-22, the use of compressed engine bleed air to drive the separation process is not desirable
  - especially in landing zones that throttle back the compressor
  - However, there is plenty of electrical energy
- For this reason, an electrochemically driven inerting system was developed by Reactive Innovations
  - Uses a collection of membrane and electrode assemblies to remove the oxygen from the fuel and air mixture

Technology Behind Reactive's Oxygen-Fuel Separation System



Tubular Cell Approach

- Arrays of tubular cells give higher surface to volume ratios minimizing size, mass, and cost
- Minimizes flow conduits and eliminates stack compression assemblies



Advantages

- Uses an electrochemical potential to separate O_2 from air catalytically
- No compressor required
- Lightweight cells that are combined into arrays increase separation rate

Theory of Operation

- In theory, oxygen is not pumped through the membrane, but is transported through the membrane as a water molecule
- Pertinent reactions are:
  - Cathode: $O_2 + N_2 + 4H^+ + 4e^- \rightarrow 2H_2O_{(l)} + N_2$
  - Anode: $2H_2O_{(l)} \rightarrow O_2 + 4H^+ + 4e^-$

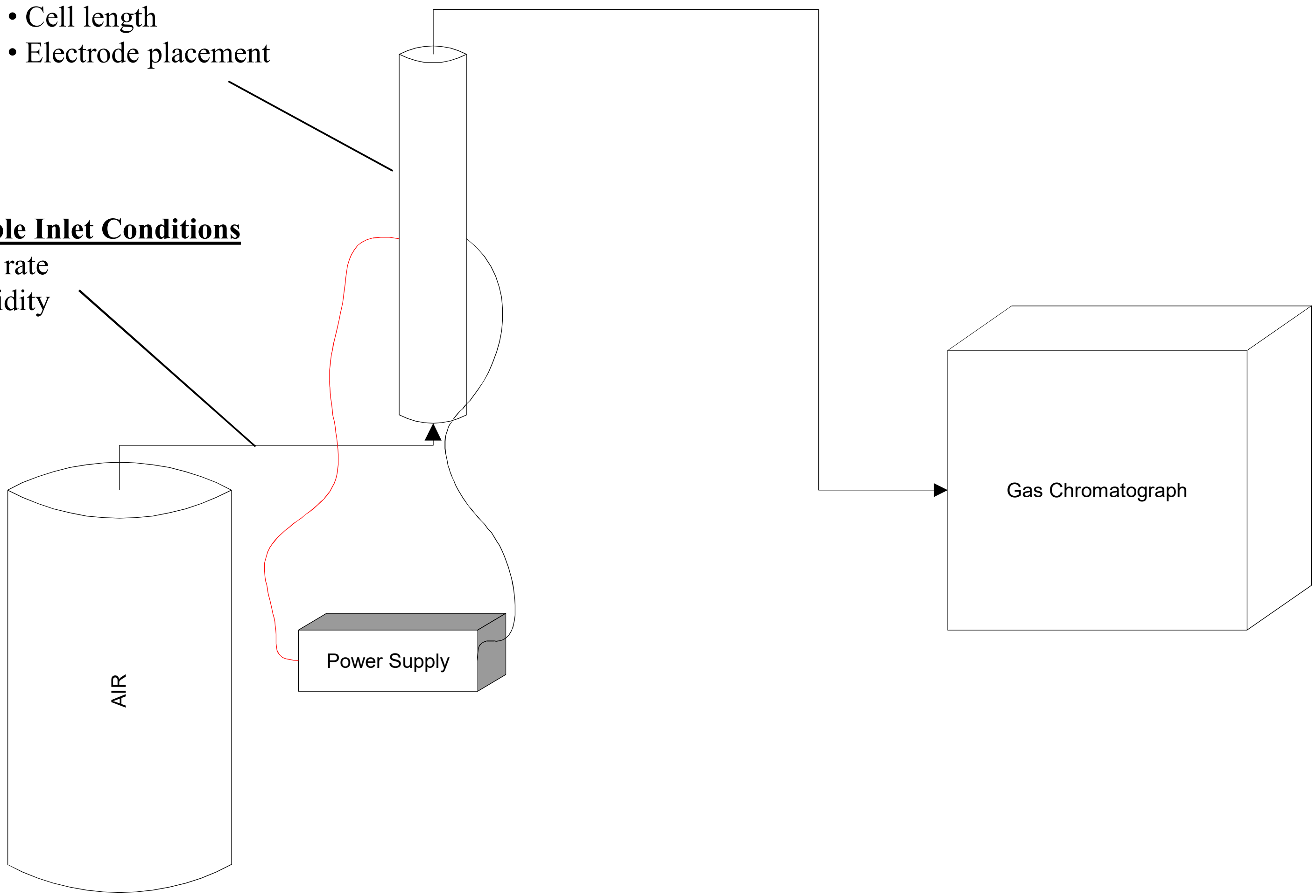
- The water used in this process is ideally balanced so that no outside water will be required
  - Electro-osmotic drag of water from anode to cathode
  - Water diffusion from cathode to anode

- This requires operating the separator at a selected current density to manage these opposing transport rates AND
  - Not producing hydrogen gas that consumes water

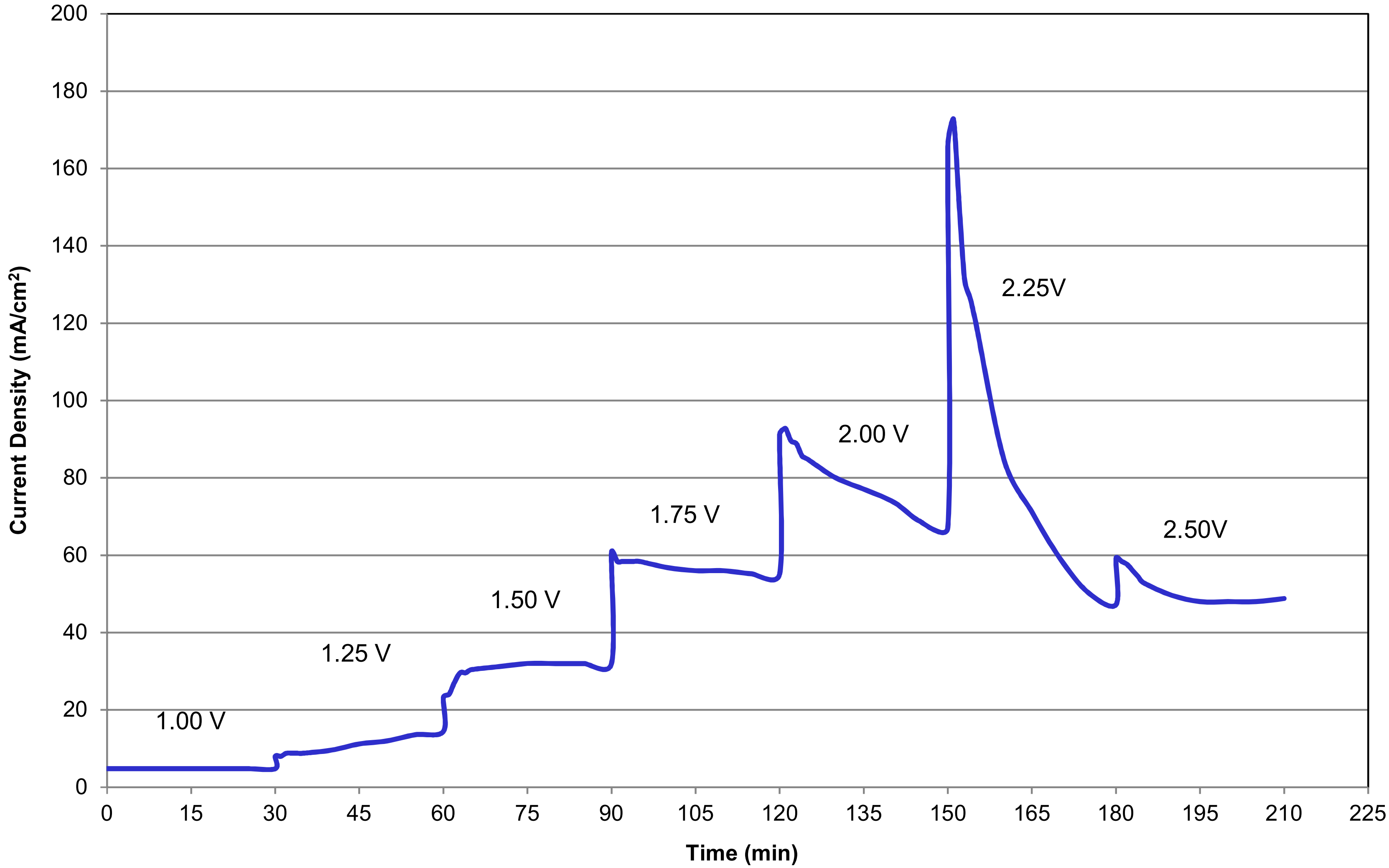
Experimental Setup

Cell Variables
- Membrane Catalyst
- Cell length
- Electrode placement

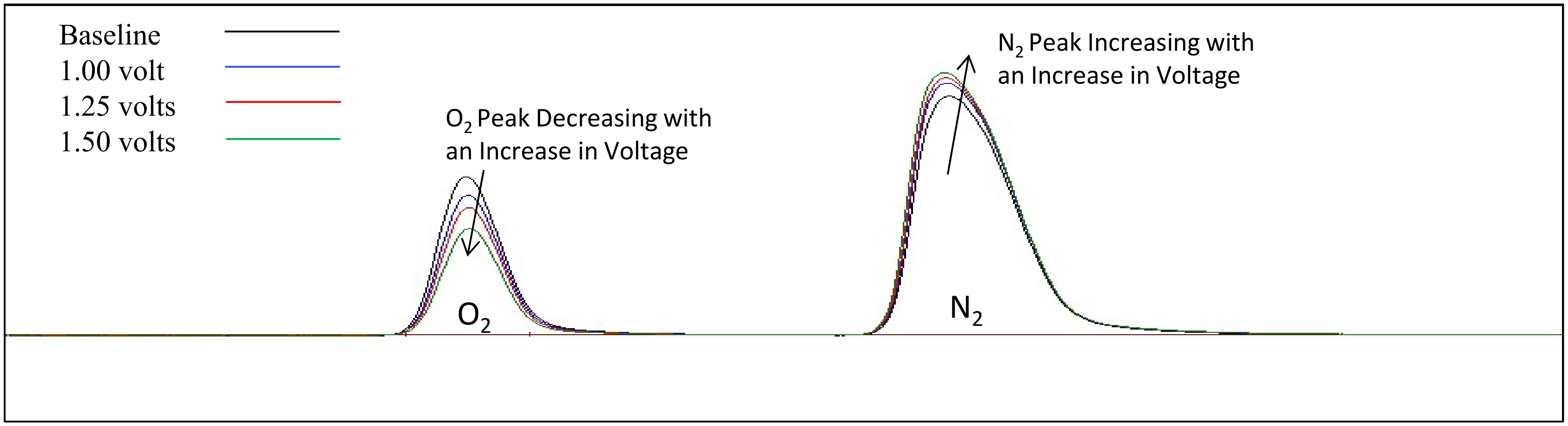
Variable Inlet Conditions
- Flow rate
- Humidity



Current Stability at Varying Applied Potentials for Electrochemically Separating Oxygen



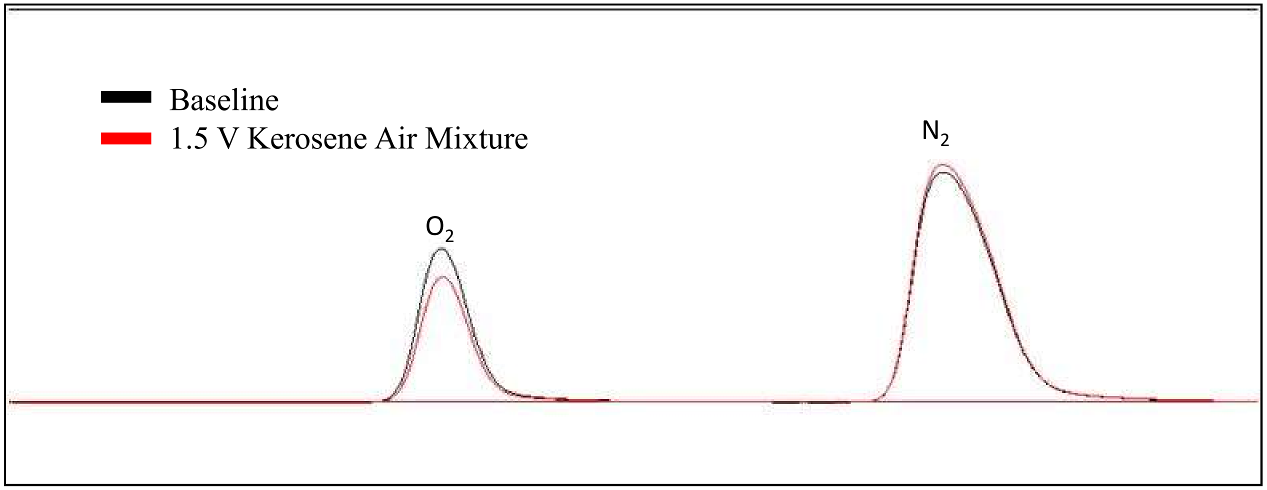
Gas Chromatography Analysis of Cathode Effluent Shows N_2 Enrichment (Air-Fed)



- Single Tubular Cell
- 13.74 cm^2 active area
- Air flow rate of 4.4 ml/min

	From GC Areas		
Trial	***Peak Area***	***O2 %***	***% O2 Reacted***
Baseline	42444.94	21.00%	-
1.00 volt	36715.11	18.11%	13.76%
1.25 volts	32945.78	16.25%	22.62%
1.50 volts	27056.53	13.35%	36.43%

Separator Performs for Enriching N_2 in Kerosene-Air Mixtures



Test Setup

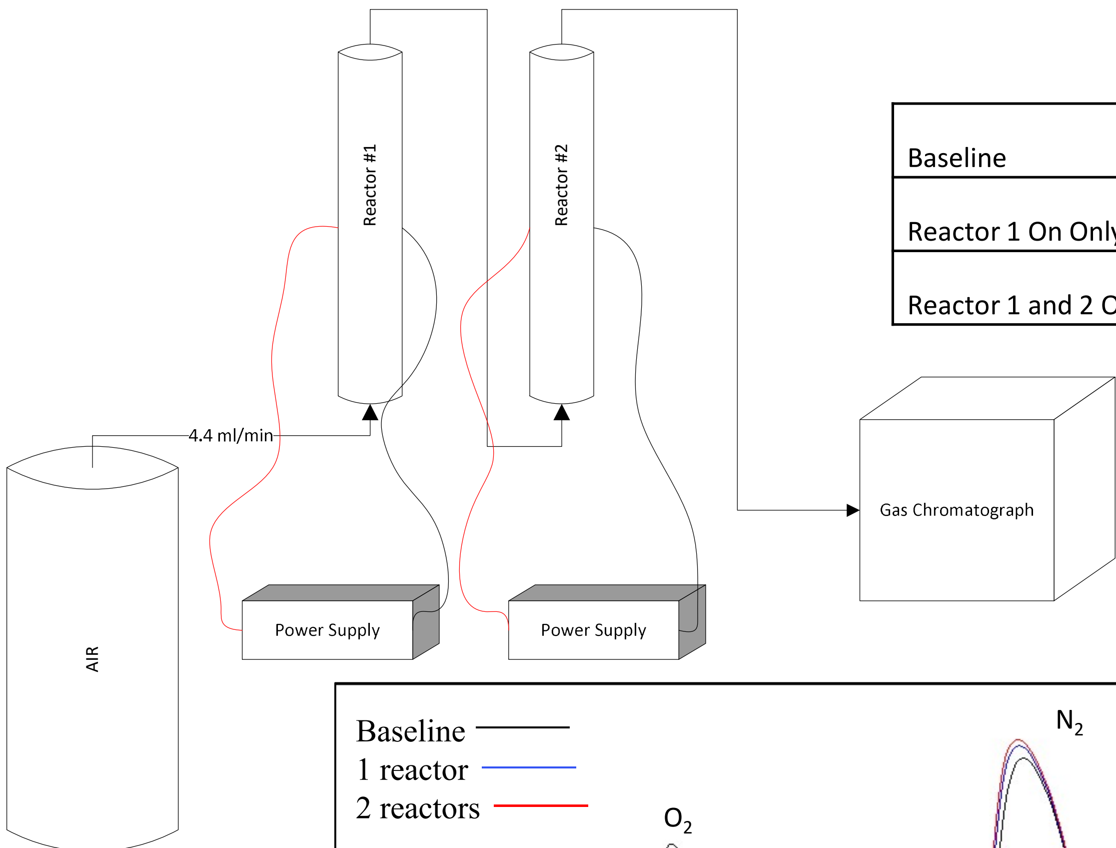
- Bubbled air through kerosene into cell cathode
- One 6" long cell

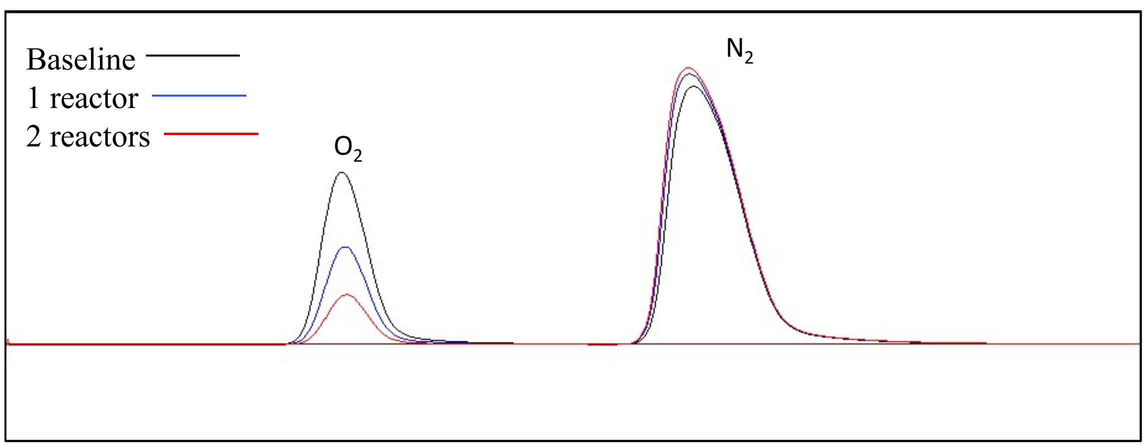
	From GC Areas		
Trial	***Peak Area***	***O2 %***	***% O2 Reacted***
Baseline (kerosene air)	34722.07	21.00%	-
1.0 volts (kerosene air)	30959.14	18.72%	10.84%
1.25 volts (kerosene air)	30059.02	18.18%	13.43%
1.5 volts (kerosene air)	27742.53	16.78%	20.10%
1.75 volts (kerosene air)	23758.54	14.37%	31.58%

*H2 present in cathode stream outlet

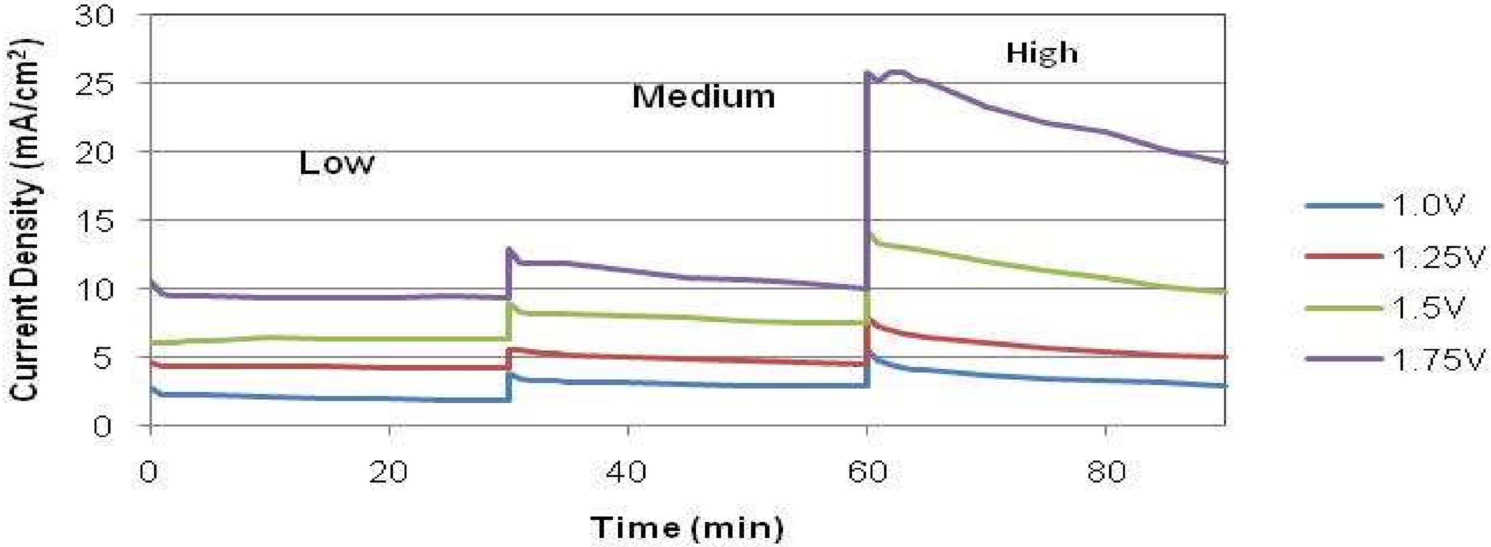
Cascaded Design Shows Even Higher N_2 Enrichment

	From GC Areas		
	Peak Area	*O2 %*	*% O2 Reacted*
Baseline	45289.56	21.00%	-
Reactor 1 On Only	24390.69	11.31%	46.14%
Reactor 1 and 2 On	11986.33	5.56%	73.52%



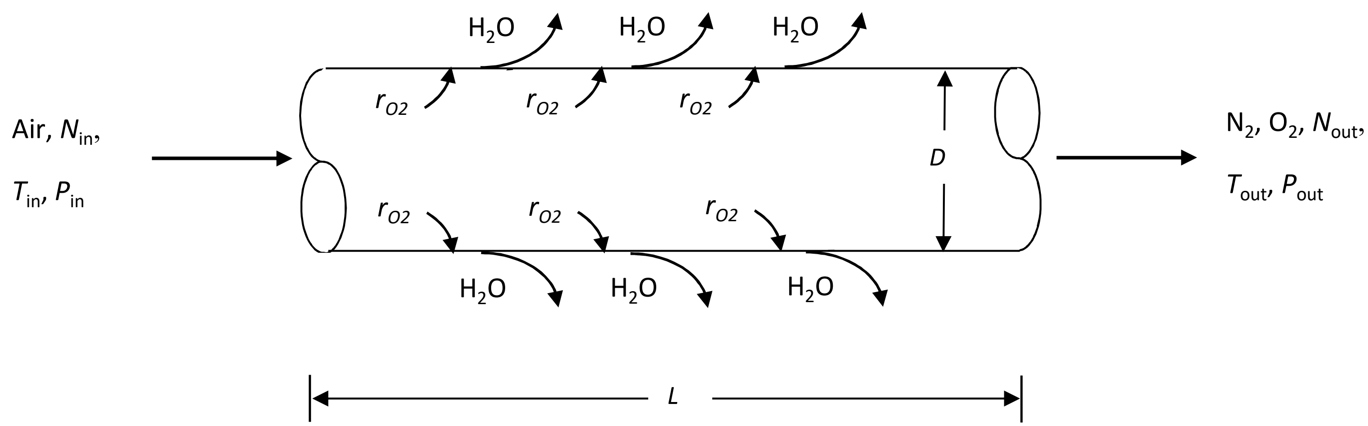


Near Stoichiometric Flow Rates Give Stable Operating Performance



Case	Percent O_2 Removed	Air Flow Rate (ml/min)		Stoichiometric Factor
		Actual	Required	
1.0V, Low	20.6%	2.0	0.9	2.2
1.0V, Med	3.2%	20.0	1.4	14.2
1.0V, High	0.3%	200.0	1.5	136.8
1.25V, Low	33.4%	2.9	2.1	1.4
1.25V, Med	3.5%	2.92	2.2	13.0
1.25V, High	0.4%	292.0	2.5	115.9
1.5V, Low	32.9%	4.4	3.2	1.4
1.5V, Med	3.9%	44.0	3.7	11.8
1.5V, High	0.5%	440.0	4.9	90.2

Mathematical Model Developed to Predict O_2 Removal in an Electrochemical Plug Flow Reactor



1) $r_{O2} = \dfrac{j \cdot a_s}{nF}$

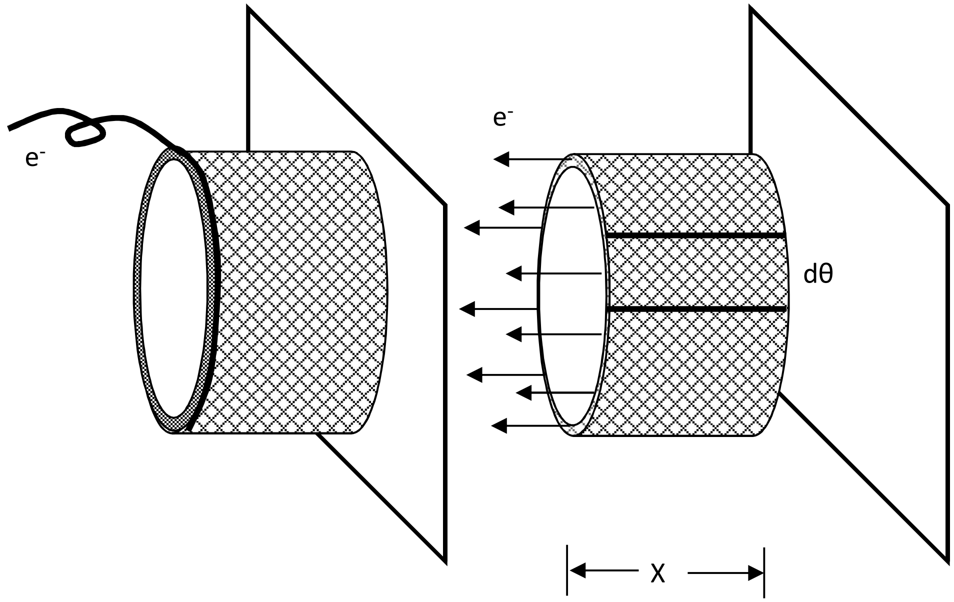
2) $\dfrac{\partial C_i}{\partial t} = -\nabla \bullet N_i - r_i$

3) $N_i = -z_i u_i F C_i \nabla \phi - D_i \nabla C_i + C_i \bar{v}$

4) $C_{O_2}(x) = C_{O_2}^{in} - \dfrac{a_s j}{nFv} x$

Case	Cell Voltage (V)	Cell Current (A)	Inlet Air Conditions: Oxygen Content (%)	Inlet Air Conditions: Air Flow (ml/min)	% O2 Removed: Measured	% O2 Removed: Predicted
A	1.00	0.0396	21.0	4.4	13.8%	16.3%
B	1.25	0.0604	21.0	4.4	22.6%	24.8%
C	1.50	0.0868	21.0	4.4	36.4%	35.7%
D	1.50	0.0884	21.0	44.0	3.0%	3.6%
E, 1st Cascade	1.50	0.0904	21.0	4.4	46.1%	37.2%
F, 2nd Cascade	1.50	0.0556	11.3	4.4	73.5%	69.0%

Voltage Distribution Modeling to Help Optimize Current Distribution in Tubular Cells



Electron flow along the current collector wire

Electron flow along the catalyst layer

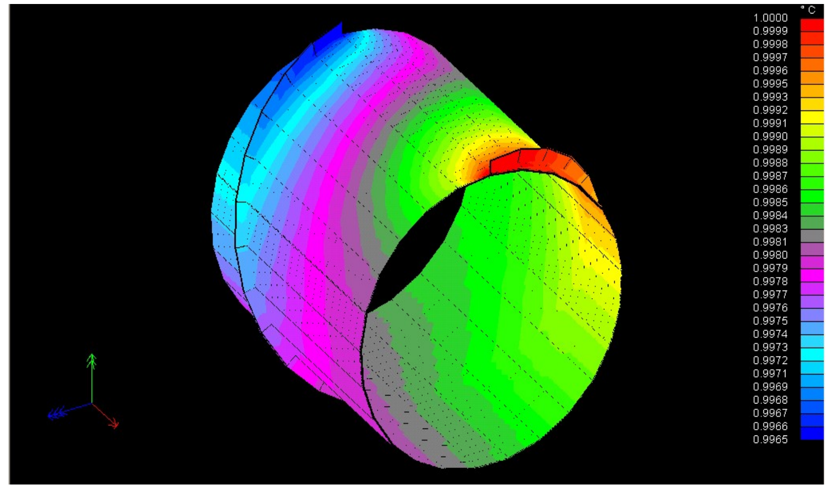
$$Q = Ak\nabla T$$

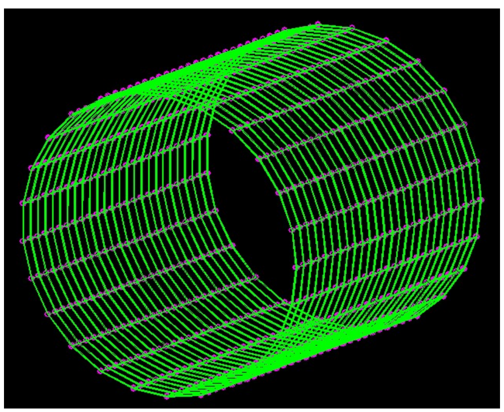
$$I = A\sigma\nabla V$$

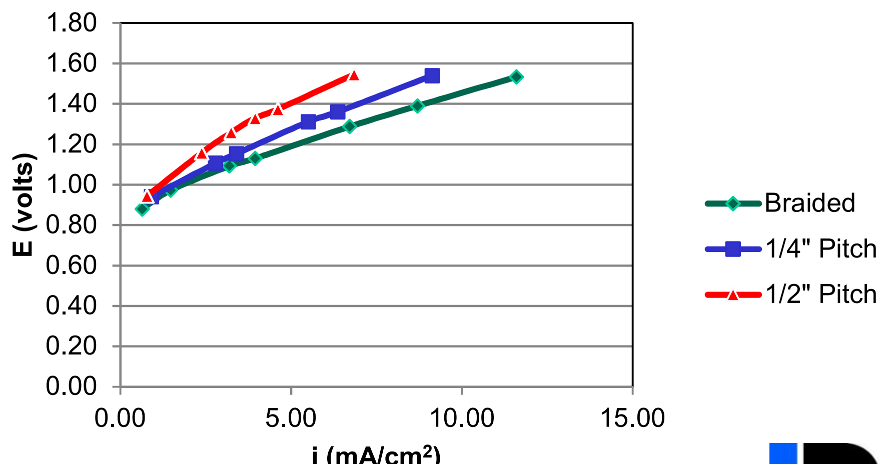
$$I = A\sigma\left(\frac{\partial V}{\partial x} + \frac{\partial V}{\partial y} + \frac{\partial V}{\partial z}\right)$$

Voltage Drops Across 6" Long Cells for Different Current Collector/Electrode Designs

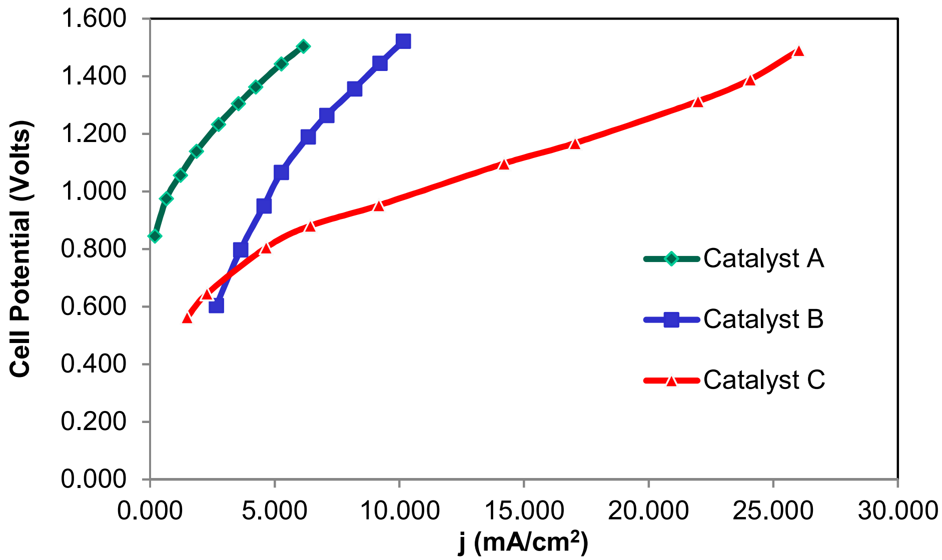
Case	No. of CC Wires	Braid Pattern	Conducitivies (S/cm)		Voltage Drop (V)
			Wire	Pt Film	
1	1	-	384615	3571	0.19
2	2	Co-Linear	384615	3571	0.10
3	2	Co-Linear	384615	1905	0.10
4	1	-	384615	1905	0.20
5	1	-	617222	3571	0.13
6	2	Co-Linear	617222	3571	0.07
7	2	Co-Linear	617222	1905	0.07
8	1	-	617222	1905	0.13
9	1	-	264583	3571	0.27
10	2	Co-Linear	264583	3571	0.14
11	2	Co-Linear	264583	1905	0.15
12	1	-	264583	1905	0.28
13	2	Cross-Braided	384615	3571	0.09
14	4	Cross-Braided	384615	3571	0.07

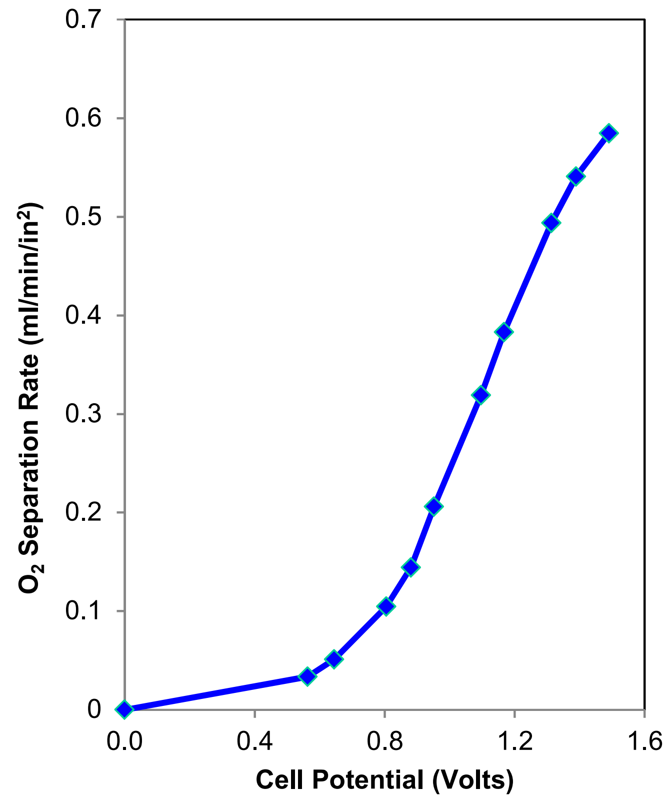






Optimized Catalysts, Cell Design, and Operating Conditions for Removing O_2 Electrochemically From Fuel Tank Ullage





- Ambient temperature and pressure
- Hydrated membrane is the only water source
- 30 mA/cm^2 is present limit that shows stable performance and no hydrogen gas evolution @ 1.5 volts

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For More Information:

Michael C. Kimble, Ph.D.
President & Founder
Reactive Innovations, LLC

mkimble@reactive-innovations.com
(978) 692-4664
www.reactive-innovations.com