IPRO 318: Fuel Cells for the Future

Business or Bust?

- Survey different types and study fundamental working principles of Polymer Electrolyte Membrane (PEM) fuel cells, and evaluate the commercial feasibility of fuel cell powered automobile
- Select and study in depth one specific type of PEM fuel cell, and propose possible utilization in military applications
- Select an application and create a design incorporating a PEM fuel cell system and perform a cost and benefit analysis using engineering design principles

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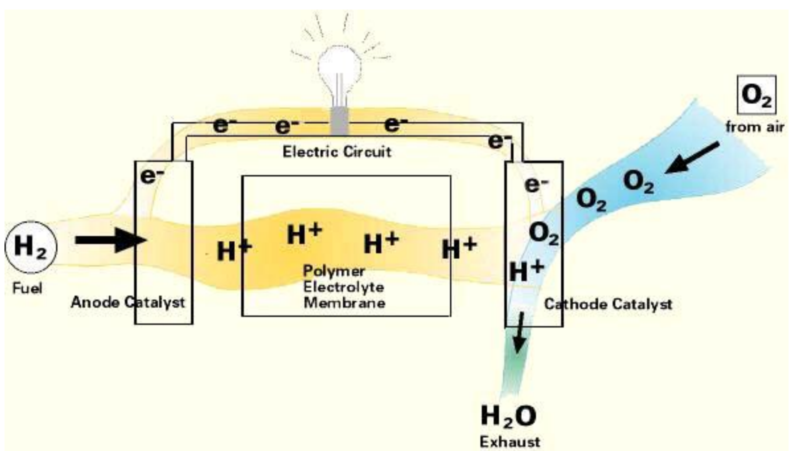
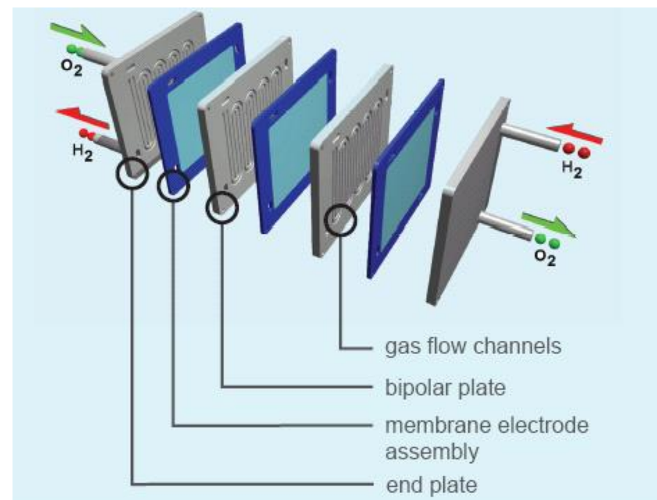
- Research Objectives
- Background
- Ethical Issue
- Phase I Research
- Phase II Research
- Phase III Research
- Conclusion
- Acknowledgement
- Questions

- Fuel cell- electrochemical conversion device that produces electricity through the oxidation of fuel
- Polymer Electrolyte Membrane(PEM)- specific type of fuel cell with solid polymer membrane





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- •Research Objectives
- •Background
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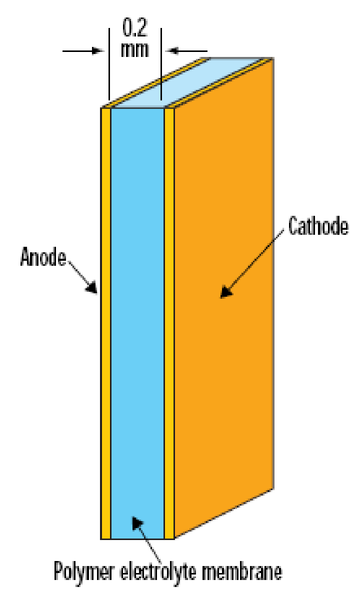
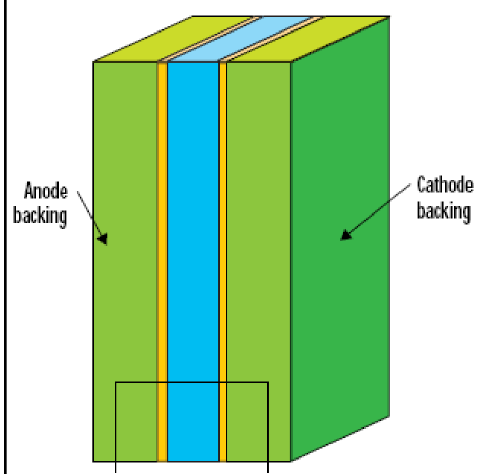
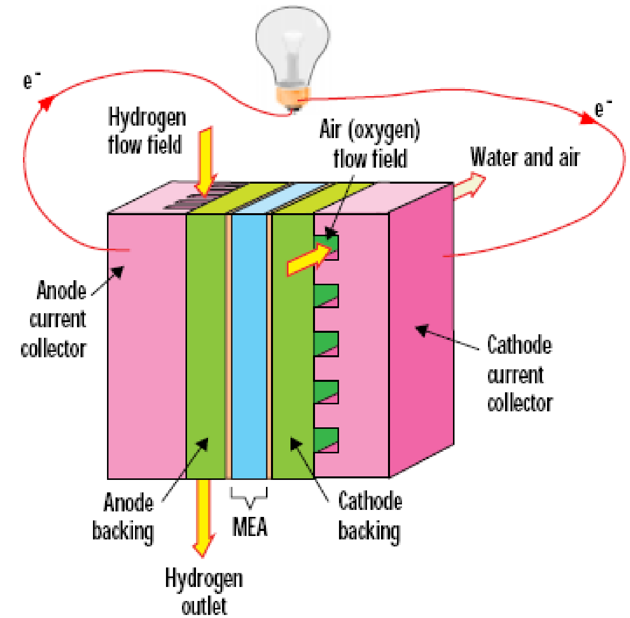


Membrane/electrode assembly

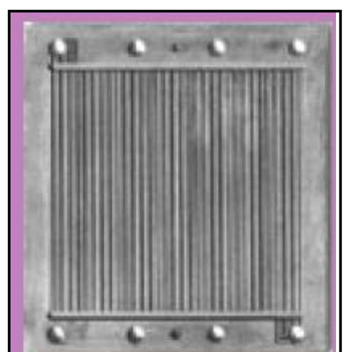
MEA

Membrane/electrode assembly with backing layers.





A single polymer electrolyte membrane fuel cell.



Charge collector/
Bipolar plate

Ethical Issues

- Improper citation of published work
- Not listening to others' ideas
- Not working as a team
- Overlooking safety or environmental aspects
- Unequal share of work

Phase I Research

❖Tasks

❖Methodology

❖Results

❖Updated objective

- Study different fuel types and reforming reactions
- Study impurities and their impact on cell performance, particularly catalyst poisoning
- Perform cost analysis on fuel cell and fuels and compare with internal combustion engine for automobile application

Phase I Research

❖Tasks

❖Methodology

❖Results

❖Updated objective

- Cost Analysis Team:
  - Cost of fuel cell
  - Cost of combustion engine
  - Cost of gasoline
  - Production cost of hydrogen from CH_4
  - Cost of JP-5,JP-8 jet fuels
- Fuel Analysis Team:
  - Storage and transportation of hydrogen
  - Water Gas Shift reaction (WGS)
  - Preferential oxidation,
  - Catalytic reforming, JP-5, JP-8,
  - Steam Methane Reforming (SMR),
  - Desalination and Electrolysis for Hydrogen production
- Impurities Analysis Team:
  - Membrane failure
  - Impurities' effects on anode, cathode, polymer electrolyte, and catalyst

Cost (112 kW):

Internal combustion engine = $3360.

Fuel cell = $200/kW = $22400

Cost H_2/gal from:

Methane	$1.98/gal*
Gasoline	$1.89/gal
JP-8	$2.34 to $3.13/gal
JP-5	$2.94/gal

Hydrogen Yields from:

Methane	75%
Gasoline	85%
JP-8	13.81% Hydrogen Hydrocarbons C9-C16 Energy density: 2000-3700 Wh/kg
JP-5	14.1% Hydrogen

Phase I Research

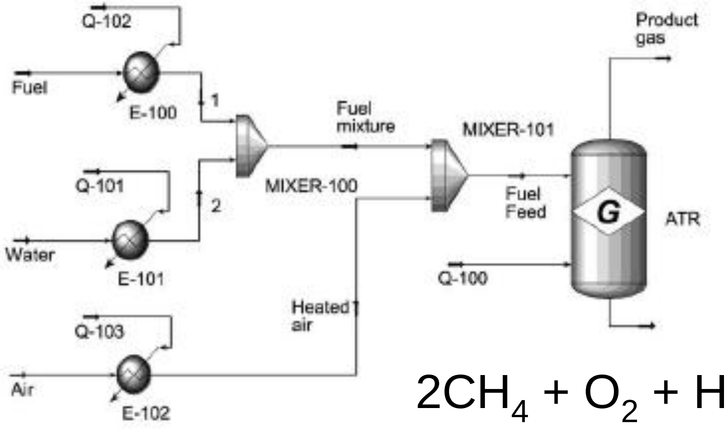
❖Tasks

❖Methodology

❖Results

❖Updated objective

Autothermal (ATR) Fuel Reforming: vaporized hydrocarbon fuel, air and water (steam) are fed at controlled conditions to the reactor to produce the reformate gas mixture, major inlet mixture CH_4, H_2O, O_2, and N_2, and outlet major components H_2, H_2O, N_2, CO_2, and CO



$$2CH_4 + O_2 + H_2O \rightarrow 5H_2 + 2CO$$

Catalytic Reforming: converts low octane hydrocarbons into high-octane products, producing hydrogen as byproduct

Steam Methane Reforming (SMR): Methane reacting with steam at 750-800°C (1380-1470ºF) to produce a synthesis gas (syngas), a mixture primarily made up of hydrogen (H2) and carbon monoxide (CO), which then undergoes Water Gas shift reaction:

$$CH4 + H2O \rightarrow CO + 3\ H2$$

$$CO + H2O \rightarrow CO2 + H2$$

Phase I Research

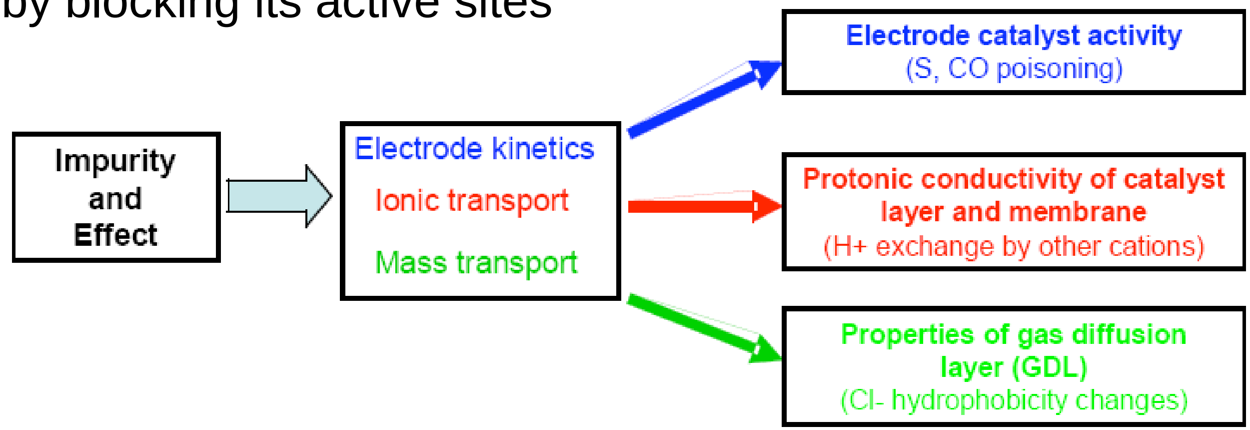
- ❖Tasks
- ❖Methodology
- ❖Results
- ❖Updated objective

Oxidation half reaction	$2H_2 \rightarrow 4H^+ + 4e^-$	→ Anode Side
Reduction half reaction	$O_2 + 4H^+ + 4e^- \rightarrow 2H_2O$	→ Cathode Side
Cell reaction	$2H_2 + O_2 \rightarrow 2H_2O$	

•The catalyst platinum (Pt) works best for both the oxidation and reduction half reactions, and therefore is used on both the anode and cathode.

•The multi-step electron reduction process at the cathode is more than 100 times slower than the H_2 oxidation half reaction

•CO is the most important impurity, it will poison the Pt catalyst by blocking its active sites



Phase I Research

❖Tasks

❖Methodology

❖Results

❖Updated objective

Fuel cell powered automobile deemed commercially unfeasible for mass market, shifting attention to specialized application in military:

- Researched feasibility of using fuel cell in Unmanned Underwater Vehicles (UUV's)
- Researched feasibility of using a fuel cell to power Unmanned Aerial Vehicle (UAV)
- Researched the phosphoric acid-doped polybenzimidazole membrane (PBI) fuel cell, a high temperature PEM fuel cell

Phase II Research

❖Methodology

❖Results

❖Updated objective

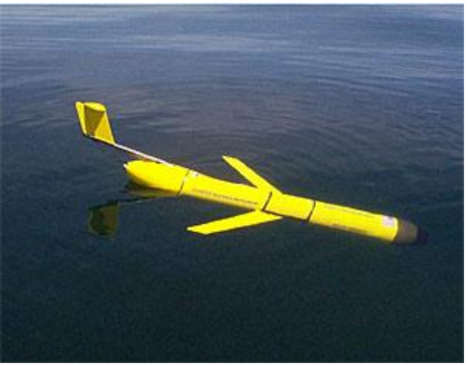
- Unmanned Underwater Vehicles (UUV) Team:
  - -UUV background
  - -Fuels used in UUV's
  - -Advantages and disadvantages of using fuel cells in UUV's
- Unmanned Aerial Vehicle (UAV) Team:
  - -History of UAV's
  - -Existing UAV designs and specifications
  - -Functions and classifications of UAV's
- Polybenzimidazole membrane (PBI) fuel cell Team:
  - -Fuel cell materials: carbon backing and support layers, bipolar plates
  - -Synthesis of PBI/phosphoric acid membrane, catalyst
  - -PBI fuel cell's susceptibility to impurities and poisoning

Phase II Research

❖Methodology

❖Results

❖Updated objective



- Uses of Unmanned submersibles:
  - Underwater mine warfare
  - Intelligence, surveillance and reconnaissance
  - Undersea environmental sensing and mapping
  - Trailing of enemy submarines
- Most submersibles powered by rechargeable batteries
- Advantages of using fuel cells in UUV's:
  - Extended range (higher energy density)
  - Silent operation
  - Rapid recharge (refuel reactant tanks)
- Potential problems:
  - Hydrogen and oxygen storage
  - On-board reforming

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Phase II Research

❖Methodology

❖Results

❖Updated objective

•Unmanned Aerial Vehicle (UAV) application: surveillance

•Record flight time: 96 hours continuous flight

- Eventual goal is 5 years in the air.

•Maximum altitude: 100,000 ft

- Different designs based on altitude and purpose

•Maximum speed: variable

- Depends on size and payload

•Power source depends on size:

- Small UAV's: battery
- Larger UAV's: alternating (internal combustion) engine
- Very large UAV's: jet engine

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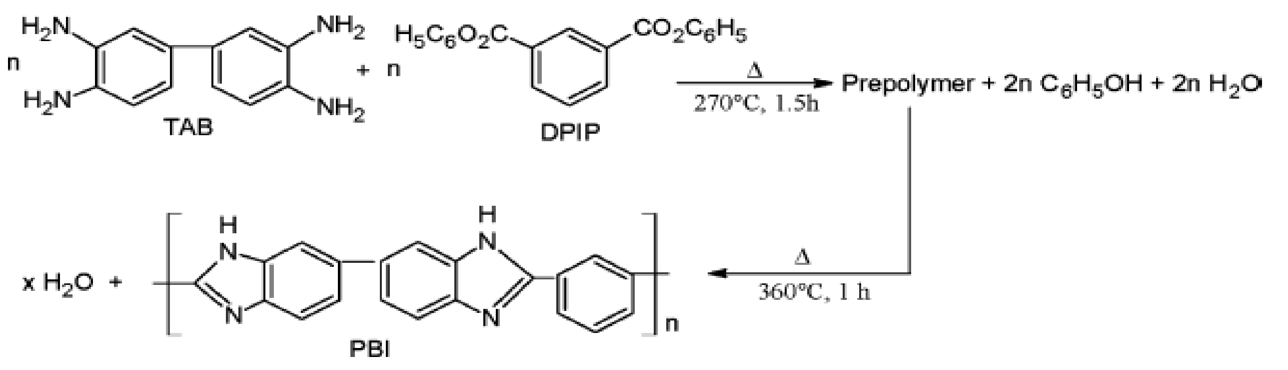
Phase II Research

❖Methodology

❖Results

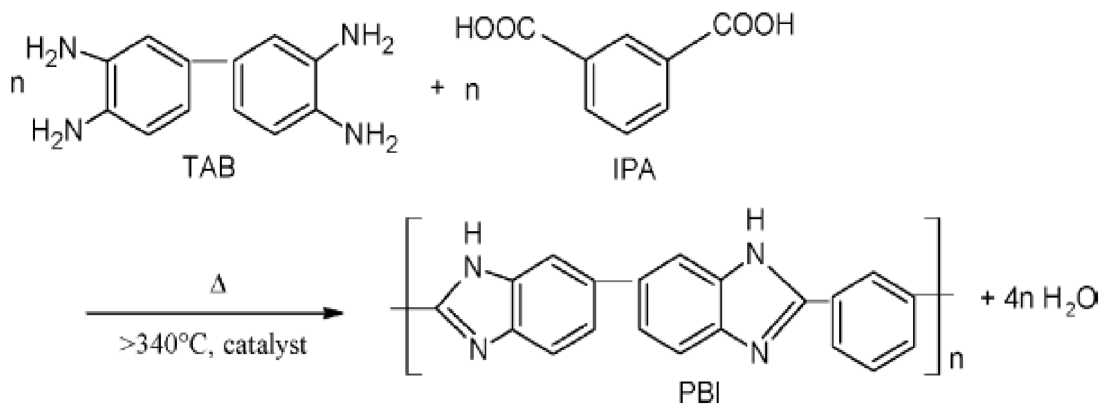
❖Updated objective



Scheme 2. The two-stage process for PBI synthesis.

• PBI refers to aromatic heterocylic polymers containing benzimidazole units formed from combinations of tetraamines and diacids.

• Specifically, it refers to the commercial product under the trademark Celazole®, poly 2,2-*m*-(phenylene)-5,5-bibenzimidazole



Scheme 3. The single-stage process for PBI synthesis.

Phase II Research

- Methodology
- Results
- Updated objective

- Advantages of PBI membrane compared to Nafion®
  - No humidification necessary
  - Operates at 160 to 200°C
    - Nafion® based fuel cells operate below 100°C to maintain humidification
  - Less cooling
  - Tolerance for CO is increased from 30ppm to 3%
    - Reformed hydrogen can be used directly from a methanol reformer without additional cleanup
    - Eliminates 48% drop in voltage output from CO contamination
- Bipolar plates serve as flow fields and current collectors
  - Graphite bipolar plate has good corrosion resistance
  - Metal bipolar plate has higher conductivity and lower cost

UAV selected as the application for fuel cell design due to easier access to atmospheric oxygen

• Survey the available plane designs and select an appropriate model to retrofit with fuel cell system

• Design fuel cell stack, delivery and storage system

• Design aerodynamically balanced placement for fuel cell, fuel, and motor.

• Design electronic system to work with the fuel cell

Fuel Cell Design Team

- Design the fuel cell system to power the selected plane and system to store, transport, and reform the fuel

Transformers Team

- Design the power system to supply power to the motor and other accessories

Phase III Research

❖Methodology

❖Results

- Application to senior design project unsuccessful due to the small plane size
- Weight and volume limitations inhibited commercial and model aircraft use
- Most feasible choice was converting a two-man airplane into a UAV based on Cessna Skycatcher requiring 100 kW power with a weight limit of 227 kg for the fuel cell design

Phase III Research

❖Methodology

❖Results

- Chose an electric motor that provides equivalent power
  - DMI 180B selected

- Calculate the power, voltage and current requirements for the motor
  - Power required 100 kW
  - Voltage required 750 V
  - Current required 135 A
  - Shaft Speed 2,800 rpm

- Transformer and invertors necessary to get the correct voltage and current to the motor

Single Engine Skycatcher Engine

DMI 180B Motor

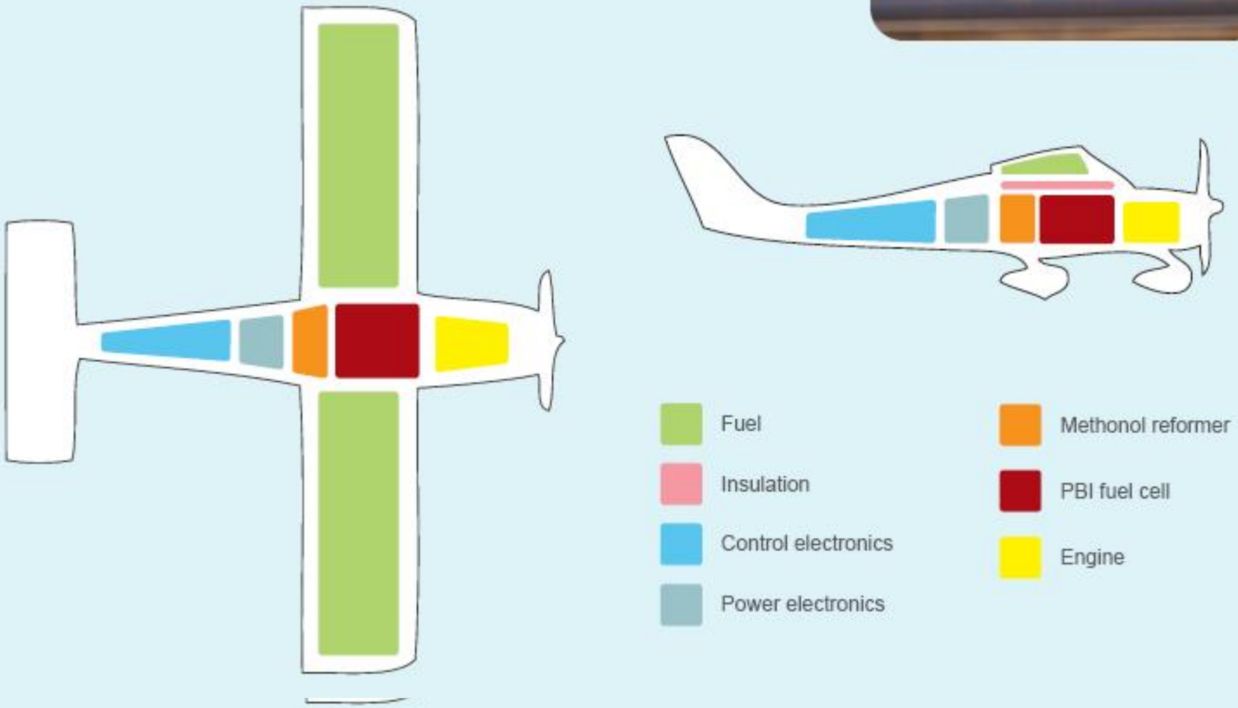
Phase III Research

❖Methodology

❖Results

cessna skycatcher

- medium size gives enough space to fit the fuel cell and all components into previous passenger space
- the fuel cell replaces the cockpit
- electronics and supporting systems fit into the storage areas
- fuel and engine spaces are used for their original purpose



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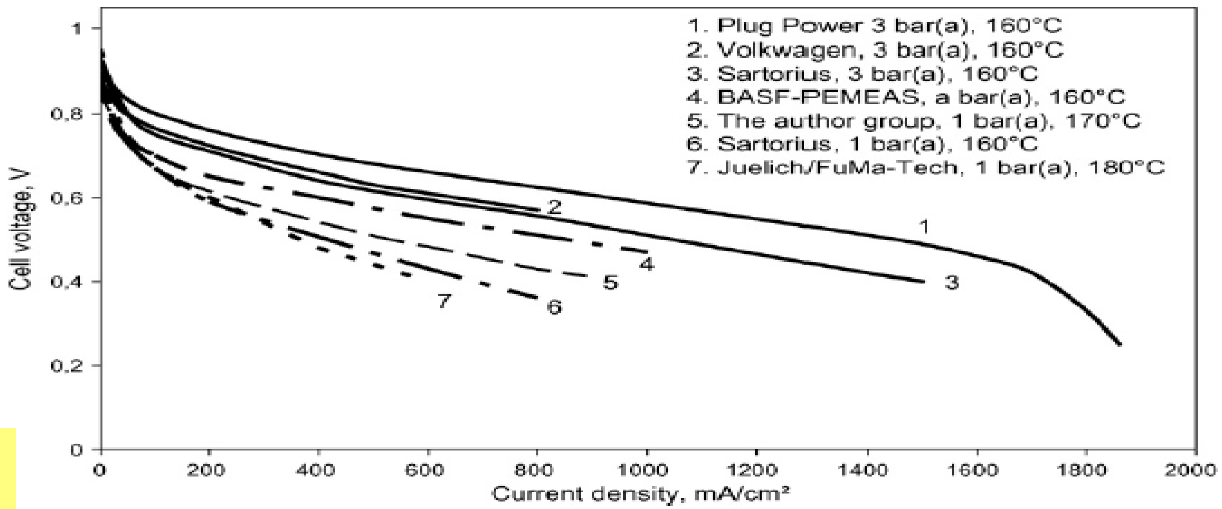
Phase III Research

❖Methodology

❖Results

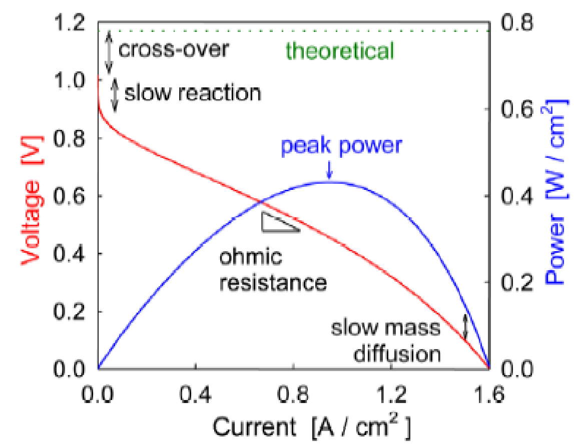
Polarization curves of PBI cells operating with hydrogen and air at 160–180 ◦C.



$\Delta G = \Delta H - T\Delta S$
$= -285{,}800\ J - (298\ K)(-163.2\ J/K)$
$= -237{,}200\ J$

$\Delta E = -\Delta G/nF$
$= -(-237{,}200\ J/2 \times 96{,}487\ J/V)$
$= 1.23\ V$

❖Activation Loss
❖Ohmic loss
❖Mass transport loss due to depletion of reactants at catalyst sites



@ 160 C, delta E =-1.11V

Operating Voltage: 0.6 V

Effiency: 54%

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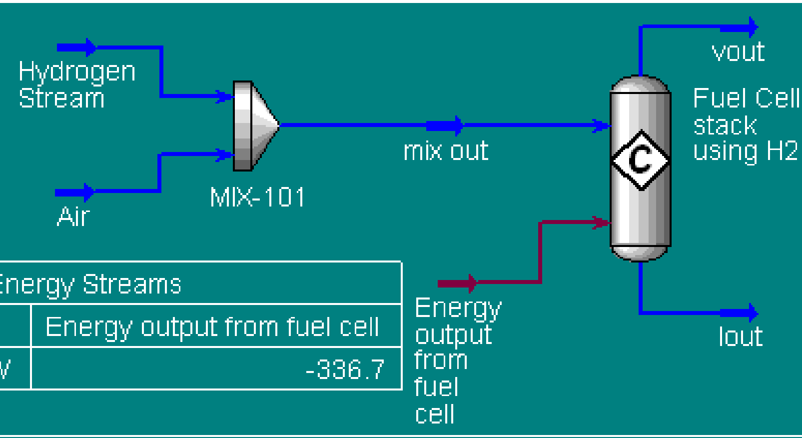
Phase III Research

- ❖Methodology
- ❖Results

Using compressed H_2:



Energy Streams		
		Energy output from fuel cell
Heat Flow	kW	-336.7

Material Streams						
		Hydrogen Stream	Air	mix out	vout	lout
Vapour Fraction		1.0000	1.0000	1.0000	1.0000	0.0000
Temperature	C	160.0	160.0	171.1	160.0	160.0
Pressure	kPa	6.895e+004	57.16	57.16	57.16	57.16
Molar Flow	kgmole/h	4.980	11.87	16.85	14.36	0.0000
Mass Flow	kg/h	10.04	342.6	352.6	352.6	0.0000
Liquid Volume Flow	m3/h	0.1437	0.3960	0.5397	0.4159	0.0000
Heat Flow	kW	6.876	13.16	20.03	-316.7	0.0000

Phase III Research

❖Methodology

❖Results

Cockpit Dimensions	119	112	176 cm
Current Density	0.4 A/cm^2		
Cell Voltage	0.6 V/MEA		
Bipolar Plate Thickness	0.1 cm		
Total MEA Thickness	0.4 cm		
Reduction in MEA Area	1 cm		
Flight Time	4 hours		
Temperature of Cell	160 °C		
Electricity Needed for Hydrolysis of 1 kg of H2	55 kWh		
Fuel Cell Efficiency	50 %		
Hydrogen Density	27 L/kg	at 10,000 psi	

Stacking

	# of MEAs	MEA Area (cm^2)	Voltage (V)	Current (A)	Power (kW)
	2530	247	1518	98.8	150.00
Motor Requirements			*750*	*135*	*101.25*

Farraday's Law Calculations - Amount of Hydrogen

Q (C)	F (C/mol)	M (kg/mol)	z	m (kg)	Total Mass (kg)
1422720	96485	0.00201588	2	0.01486258	37.61

$$m = \left(\frac{It}{F}\right)\left(\frac{M}{z}\right)$$

Phase III Research

❖Methodology

❖Results

Total Mass			
Component	Mass (kg)		Total Mass (kg)
Hydrogen	40.16		271.48
Catalyst/Support	8.35		
PBI	0.60		
Bipolar Plates	222.31		
Fan	0.06		

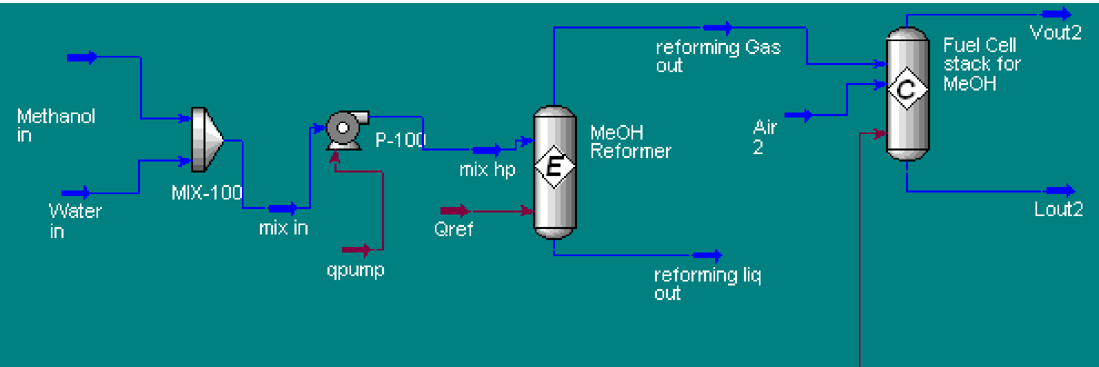
Total Cost			
			Total Cost ($)
Hydrogen	750		26574
Catalyst/Support	24876.88		
PBI	181.82		
Bipolar Plates	750.00		
Fan	15.00		

Phase III Research

❖Methodology

❖Results

Using MeOH with onboard reforming:



Energy Streams				
		Qref	qpump	Energy output from fuel cell 2
Heat Flow	kW	176.8	2.213e-002	-646.7

Material Streams										
		Methanol in	Water in	reforming Gas out	reforming liq out	mix in	mix hp	Vout2	Lout2	Air 2
Vapour Fraction		0.0000	0.0000	1.0000	0.0000	0.0000	0.0000	1.0000	0.0000	1.0000
Temperature	C	20.00	20.00	280.0	280.0	16.91	16.93	160.0	160.0	160.0
Pressure	kPa	101.3	101.3	380.0	380.0	101.3	380.0	57.16	57.16	57.16
Molar Flow	kgmole/h	3.210	4.820	14.45	0.0000	8.030	8.030	33.99	0.0000	24.23
Mass Flow	kg/h	102.9	86.83	189.7	0.0000	189.7	189.7	888.6	0.0000	699.0
Liquid Volume Flow	m3/h	0.1293	8.701e-002	0.4707	0.0000	0.2163	0.2163	1.046	0.0000	0.8080
Heat Flow	kW	-217.0	-382.8	-423.0	0.0000	-599.8	-599.8	-1043	0.0000	26.85

Phase III Research

❖Methodology

❖Results

Stacking

# of MEAs	MEA Area (cm^2)	Voltage (V)	Current (A)	Power (kW)
5088	247	3052.8	98.8	301.62
Motor Requirements		*750*	*135*	*101.25*

Farraday's Law Calculations - Amount of Hydrogen

Q (C)	F (C/mol)	M (kg/mol)	z	m (kg)	Total Mass (kg)
1422720	96485	0.00201588	2	0.0148626	75.62

Component	Mass (kg)
Methanol	411.6
Water	347.32
Catalyst	9.61
PBI	1.21
Bipolar Plates	727.49
Methanol Reformer	1139.74
Pump	77.11
Total	**2714.08**

Component	$
Methanol	82.42
Catalyst	50862.36
PBI	365.60
Bipolar Plates	94255.20
Methanol reformer	92,500
Pump	16400.00
Total	**254465.58**

• Two PBI fuel cell systems were developed to power Cessna Skycatcher using:

- Compressed hydrogen
- Onboard reforming of methanol

• Calculations showed the weight and space required for onboard reforming exceeded the design limitations

• Compressed hydrogen fuel cell system has more potential

-Future work is needed to resolve the heat dissipation issue

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- MMAE 436 (Screech Owl) design team
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Backup Slides

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Fuel Cell Heat — Compressed H2

Efficiency	0.49	
Total Energy	1212202	kJ/h
Heat Energy	620884	kJ/h
Heat Transfer Coefficient	14	W/m^2 K
Log Mean Temperature	338.58	K
Needed Heat Transfer Area	464902616	m^2
	465	km^2

Fuel Cell Heat — MeOH reforming

Efficiency	0.49	
Actual Process Enthalpy	4211	kJ/kgmol
Theoretical Process Enthalpy	8632.55	kJ/kgmol
Molar Flow Rate	33.93	kgmol/h
Total Energy	292902.42	kJ/h
Heat Energy	150023.19	kJ/h

Graphite Bipolar Plates — Density 1.82 g/cm^3 — Price 0.075 $/cm^2 — MeOH reforming

Volume (cm^3)	Mass of 1 Plate (kg)	Mass for All (kg)	$
78.546	0.14	727.49	94255.2

Metal Bipolar Plates — Density 8.00 g/cm^3 — Price — Compressed H2

Volume (cm^3)	Mass of 1 Plate (kg)	Mass for All (kg)	$	Price	
16.47	0.13	222.31	750	$5/kW	Stainless Steel Core - Nitrided
				$35/kW	Au plated Al

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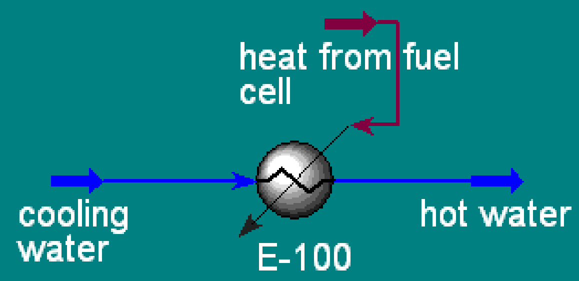

Energy Streams		
		heat from fuel cell
Heat Flow	kW	186.0

Material Streams			
		cooling water	hot water
Vapour Fraction		0.0000	1.0000
Temperature	C	20.00	1756
Pressure	kPa	101.3	101.3
Molar Flow	kgmole/h	5.551	5.551
Mass Flow	kg/h	100.0	100.0
Liquid Volume Flow	m3/h	0.1002	0.1002
Heat Flow	kW	-440.9	-254.9