

**IPRO 318**  
**Fuel Cells for the Future**

*Business or Bust?*

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Kathleen Baker  
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Elizabeth Corson  
Marisol Aguirre  
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Emily Kunkel  
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## Abstract

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This IPRO was created to address the increasing concern of energy supply. Currently used sources of energy are polluting the environment and being depleted rapidly. Thus, there must be some other means of alternative energy to power today's vehicles and appliances. Fuel cells are one possible alternative because they have the potential to be more environmentally safe, more reliable, and more energy-efficient than internal combustion engines.

The purpose of this IPRO was to evaluate the feasibility of fuel cells in commercial applications such as military and defense, automotive, and aerospace. Three main aspects of fuel cells were investigated: performance, comparison with other power sources, and incorporation of design. The team researched industrial and commercial properties of fuel cells and studied ways to improve the catalysts and reduce fuel impurities. Fuel cell performance and cost was compared and contrasted with internal combustion engines, and eventually, a design was drafted that incorporated a fuel cell system as the power source for a light aircraft using engineering design principles.

The first approach to this problem was to research the technical aspects of fuel cells. This included types of fuel cells, fuel analysis, and cost analysis. From this, it was determined that polybenzimidazole (PBI) fuel cells were the most promising.

Next, the group investigated for possible applications of a fuel cell system. Commercial automobiles were determined not to be feasible with current technology because a fuel cell engine and associated reforming processes are too heavy, not space efficient, and not cost effective. Then unmanned air vehicles (UAVs) and unmanned submersible vehicles were considered as two possible military applications. Unmanned submersible vehicles were dismissed because storage of hydrogen and oxygen would be too difficult under the high pressures encountered in the deep sea. Unmanned air vehicles were chosen as the best option because of space the and air available in aircrafts versus submersibles.

Several UAV designs were considered. The first design was applied to an original IIT designed aircraft by MMAE senior students, which was determined to be too small to carry the fuel cell it would require. Next, different models on the market developed by large corporations such as Boeing, Northrop Grumman, AeroVironment and General Atomics were considered, only to encounter the same difficulty as with the student-made design. As another alternative, model airplanes were investigated because their power and size requirements were easily accessible. However, replacing the battery with a fuel cell system was deemed unlikely, again due to size and weight limitations. Finally, we decided that the best possible choice was converting a two-passenger airplane into a UAV because the space and weight originally designed for two people could be easily adapted and used for the space and weight of a fuel cell power system.

This IPRO was especially difficult because the team was researching a topic that is still in its infant stages. Fuel cells are only now being put into small scale production and it is a huge leap from there into commercial and military applications. This IPRO was a challenge but still a success. All students learned about fuel cell operation and were constantly working in groups and

communicating ideas to the team. This IPRO encountered many obstacles but found ways up, over and around them as a team.

# Background

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## Sponsors

This project did not have a sponsor, but drove the majority of the design and research towards military applications of unmanned aerial vehicles (UAVs).

## Problems Addressed

The problems found to be most common for this project had to do with the fuel cell and the fuel that was used. The project addressed such problems as analyzing the performance of electrodes, confronting the high cost of materials, determining the performance and durability of fuel cells, minimizing degradation while maintaining or enhancing performance, minimizing size, and minimizing operating temperature. The fuel presented us with challenges such as lowering or eliminating emissions, producing the fuel, storing the fuel, and lowering the costs associated with the fuel. We also found that simply placing a fuel cell into a plane was not all that was needed. We were faced with the tasks of maintaining our power to weight ratios, especially in UAV applications, maximizing power in a certain volume that was designated to the fuel cell, and the task of getting the right power and voltage to the motor from the fuel cell.

## Technology

The technology and science involved in this project includes the fuel cell design, the type of fuel used by the fuel cell, the production of the fuel, the storage of the fuel, the motor that harvests energy from the fuel cell, the battery that is used before the fuel cell can warm up and to store the excess power, and the casing or storage of the fuel cell.

Polymer-electrolyte membrane (PEM) fuel cells are not a new concept, they have existed and been successfully implemented since the 1960's, for example, in the NASA Gemini program. The problem now is making the fuel cells ever more affordable, compact, and efficient for more widespread use. New technology arises continuously, but this project focuses on using existing, established technologies to create the most practical fuel cell possible at this time.

The fuel cell, in contrast to the internal combustion engine, works on the principle of converting chemical energy into electrical energy, which can then be used to run a motor, generating mechanical energy. This is far more efficient than burning the fuel to produce thermal energy (heat), which is then converted to mechanical energy. This conversion (thermal to mechanical energy) is known to have limited efficiency, even in the ideal case.

Hydrogen gas flows into the fuel cell at the anode (negative electrode), where it separates into electrons and protons with the help of a catalyst. The protons then flow through the membrane, while the electrons are repelled and must flow out through the anode. On the other side, air or oxygen is supplied to the cathode. This oxygen reacts with the protons coming through the membrane and electrons off the cathode (positive electrode) to create water by the air stream. If

the anode and cathode are connected to a load, such as a motor, an electric current will flow, powering the device.

While the total power generated depends on the area of the fuel cell, reasonable sizes of fuel cell will not generate enough power to run any significant device. In fact, most fuel cells typically generate about 0.7 volts per cell. Many fuel cells must be stacked in series to create enough power for a car.

The typical catalyst for the reaction in the fuel cell is platinum, which is extremely expensive. Platinum is already used in vehicles, but the amount of platinum needed for a fuel cell is many times greater. This has been the main hurdle for fuel cell technology. Although alternatives for platinum are being sought, none have yet been found, although some ways of reducing the amount of platinum necessary have been found somewhat effective.

Another hurdle is the storage of hydrogen, which can be resolved by producing hydrogen from hydrocarbon fuels, particularly natural gas (methane). There are several ways, including catalytic reforming and steam reforming. The reforming process requires a series of reactions that must take place at specific temperatures; most at temperatures higher than the operation temperature of the fuel cell. The reforming process also results in impurities that must be filtered out of the gas stream before entering the fuel cell, or they will render ineffective the platinum catalyst. Ironically, one of the ways of getting rid of the contaminant carbon monoxide is to use platinum as a catalyst to preferential oxidation, which essentially burns most of the carbon monoxide and a little hydrogen in the stream.

Other impurities also decrease the performance of the fuel cell. These include ammonia, excessive water vapor, sulfur and its compounds, and particulates. While research has made some leeway into eliminating the effects of these impurities, many of these means are still expensive and still do not provide optimal performance.

## **Historical Successes or Failures**

Fuel cells for use in vehicles have been around for a few years now. Even though they are very efficient and environmentally friendly, there are still problems that manufacturers face with fuel cells. Some problems that manufacturers have had with fuel cells are operating conditions, cost, safety, competition, and public acceptance. Operating conditions for fuel cells have been a problem in the past because fuel cells involve water, which freezes at a temperature at which the atmosphere frequently reaches. Attempts have been made to incorporate a pre-heating system for the fuel and the water in the cell to keep it from freezing in places such as Canada and Alaska where it is frequently below the freezing temperature of water (32 degrees F).

Cost is one of the main problems manufacturers have faced. Since platinum is usually used as the catalyst, the cost of fuel cells is relatively high for consumers. Attempts at reducing the cost have been somewhat successful, because of the use of carbon enriched platinum instead of using pure platinum. Since platinum costs so much, the use of other metals would be ideal to reduce the total cost of the fuel cell. Research into cheaper catalysts like nickel-tin nano-metal catalysts are still in progress.

Safety has been another concern for fuel cells, especially with hydrogen powered fuel cells. The hydrogen is stored in a high-pressure container in the car. Since hydrogen is a highly explosive gas, this is very dangerous. Attempts have been made to build storage devices that are highly pressurized but resistant to damage. Although this seems to be dangerous, consumers must take into consideration the risk they are already taking with a container of gasoline in their car.

Competition with other markets is also a problem that fuel cells have faced. Since car companies have been significantly improving the efficiency of their gasoline powered vehicles, fuel cells seem less necessary to consumers. Consumers seem to have flocked more towards hybrid vehicles because it is not such new technology.

Hydrogen powered fuel cells caused a problem with the distribution of hydrogen around the country, because the country is lacking in hydrogen fueling stations. This problem is being solved with the use of hydrocarbon-powered fuel cells, which uses hydrocarbons, which get converted into hydrogen on board to power the fuel cells. This has proven to be a reasonable answer to the problem, but since it still relies on fossil fuels, it is not a completely environmentally friendly solution.

Public acceptance has grown over the period of time since fuel cells have been introduced. The public has concerns about safety and reliability of this fuel system, just as they did with electric powered and hybrid cars at first. This needs to be solved by familiarizing the consumer with the new product, just like they were slowly familiarized with hybrid and electric cars.

Along with the failures and successes in the automobile industry are those of the aircraft industry, which were the main focus of this project. The greatest successes in the aircraft industry are those of fuel cell powered UAV's for military applications. A fuel cell powered UAV would have lower emissions, little to no noise, low heat signature, and can be smaller in size. As recent as April 5 of this year NRL unveiled a fuel cell powered UAV, the Ion Tiger, which ran much quieter, longer, and could carry heavier payloads using a fuel cell battery system. The Ion Tiger has scheduled a test flight, which entails a 24-hour endurance flight with a 5 pound payload.

Another success for UAV applications is the conversion of the Puma UAV, which has been in production since 2001 as a hand launched recoverable real-time reconnaissance aircraft for military applications. It also has the advantages of being able to be used out at sea, because it is waterproof. The AeroVironment Puma was developed as an alternative to the original Puma to have on board a hybrid system with a rechargeable battery and a fuel cell. The hybrid system flew for a nine hour test flight in 2008, more than tripling the original flight time of the battery only system. The new hybrid Puma did not sacrifice weight, mobility, or durability in order to be converted and is just as reliable as the original.

## **Ethical Issues**

The main ethical issue involved in fuel cells is safety. Fuel cells involve the reaction of hydrogen gas, which is highly explosive, especially when under the high pressure that is needed for the fuel

cell. High-pressure storage tanks for hydrogen must be located in the car, just like gasoline tanks in the automobiles today. It is necessary to keep the hydrogen under high pressure for storage purposes, but this makes it more susceptible to explosion. A small spark or leak could ignite the hydrogen fuel tank and the results could be fatal. Using hydrocarbons to fuel the fuel cell can reduce this high risk in storage. Although hydrocarbons such as methane are still explosive, they are much less of a safety risk than the storage of highly pressurized hydrogen gas.

However, the use of hydrocarbon-fueled fuel cells brings up the ethics behind environmental concerns. Car companies have been trying to move further away from the total use of hydrocarbons to fuel cars. By using hydrocarbons instead of pure hydrogen gas, there will be more environmental harm. Hydrocarbons in fuel cells still create emissions that are harmful to the environment; while hydrogen powered fuel cells only emit water as a waste product. In the end, the use of hydrogen is more of a safety hazard for the passenger but better for the environment, and the use of hydrocarbons is less of a safety hazard but still harmful for the environment.

### **Other Readings**

Green Power, by Office of Transportation Technologies, US DOE  
*New Material Needs for Hydrocarbon Fuel Processing* by Farrauto et. Al.  
California Fuel Cell Partnership, <http://www.cafcp.org/>

# Objectives

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1. Evaluate the feasibility of current PEM fuel cell technology in commercial applications, including military and defense, automotive, aerospace, and other areas.
2. Investigate industrial and commercial technicalities of PEM fuel cells.
  - a. Focus on classification, operation process, manufacture cost, operation cost, durability, and history or existing systems.
  - b. Focus on PBI fuel cells.
  - c. Study methods available for improving catalyst operation and reducing fuel impurities.
  - d. Study fuels available and reforming processes.
3. Compare and contrast the performance and cost of fuel cell and internal combustion engines
  - a. Focus on manufacture cost, operation cost, durability, efficiency, safety, and environmental impact.
4. Design and incorporate a PEM fuel cell system into commercial application
  - a. Select an aircraft capable of operating on a fuel cell system.
  - b. Design preliminary fuel cell system to fit the UAV of choice, fulfilling original power requirements and obeying aircraft dimensions.
  - c. Select fuel type and design storage system and supply process.
  - d. Design electrical system to supply UAV with power in the correct manner.
5. Perform a cost and benefit comparison of fuel cell and internal combustion power systems, utilizing engineering design principles

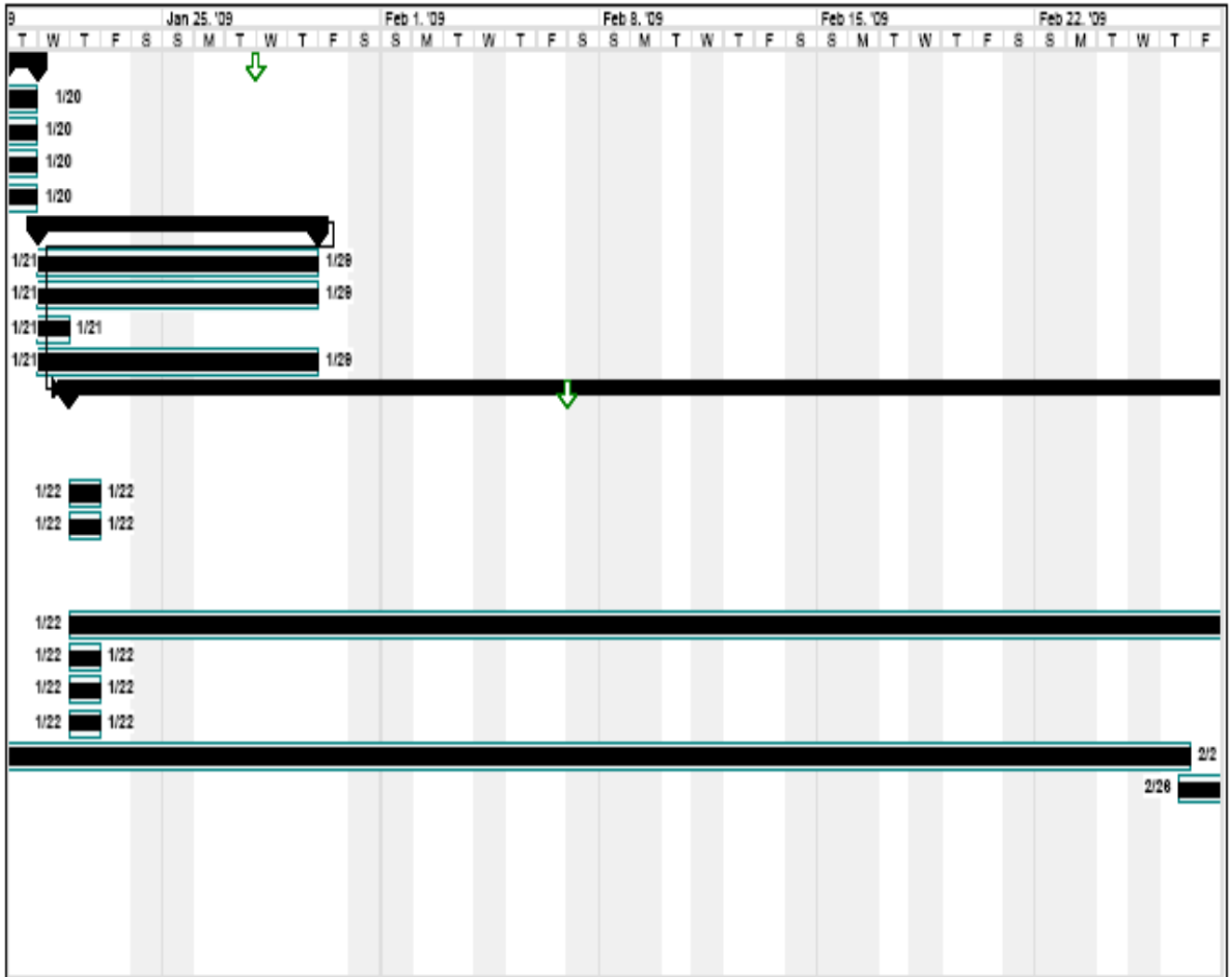


# Methodology

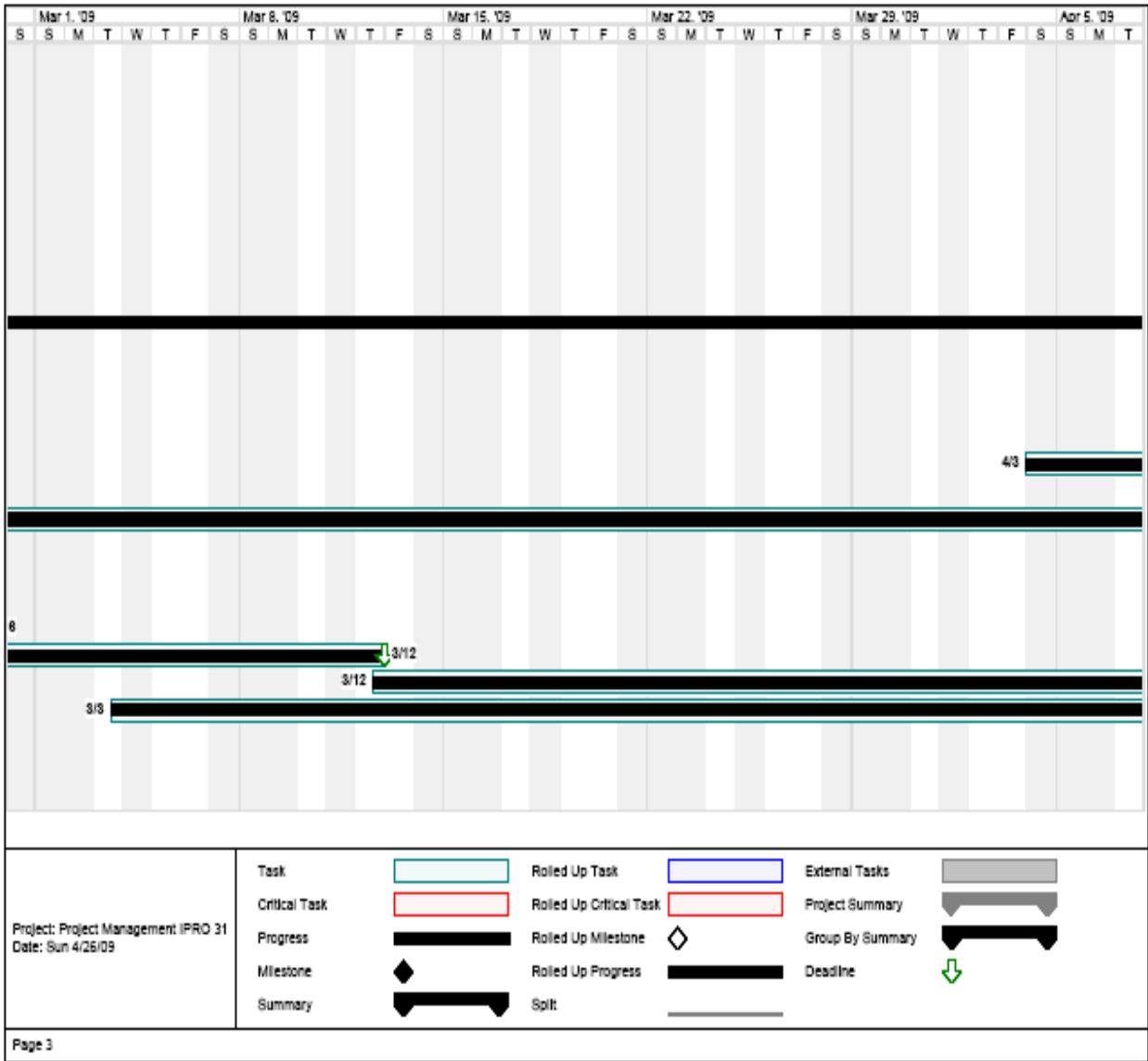
ID	Task Name	i	% Work Complete	Work	Duration	Start	Finish	9						
								T	W	T	F	S	S	M
1	Set team objectives	✓	100%	160 hrs	1 day?	Tue 1/20/08	Tue 1/20/08							
2	Evaluate the feasibility of PEM fuel cells	✓	100%	0 hrs	1 day?	Tue 1/20/09	Tue 1/20/09							1/20
3	Develop different methods	✓	100%	0 hrs	1 day?	Tue 1/20/09	Tue 1/20/09							1/20
4	Compare and contrast	✓	100%	0 hrs	1 day?	Tue 1/20/09	Tue 1/20/09							1/20
5	create a design at a commercial scale	✓	100%	0 hrs	1 day?	Tue 1/20/09	Tue 1/20/09							1/20
6	Background Research	✓	100%	1,162 hrs	7 days?	Wed 1/21/08	Thu 1/28/08							
7	Internal combustion engines	✓	100%	8 hrs	7 days?	Wed 1/21/09	Thu 1/29/09							
8	PEM fuel cells	✓	100%	8 hrs	7 days?	Wed 1/21/09	Thu 1/29/09							
9	Impurities present	✓	100%	8 hrs	1 day?	Wed 1/21/09	Wed 1/21/09							
10	costs involved in new and old infrastructure	✓	100%	8 hrs	7 days?	Wed 1/21/09	Thu 1/29/09							
11	Project Plan	✓	100%	1,776 hrs	28 days?	Thu 1/22/08	Thu 4/18/08							
12	Team Information	✓	100%	0 hrs	1 day?	Fri 4/10/09	Thu 4/16/09							
13	Team Purpose and Objectives	✓	100%	0 hrs	1 day?	Fri 4/10/09	Thu 4/16/09							
14	Background	✓	100%	0 hrs	1 day?	Thu 1/22/09	Thu 1/22/09							
15	Team Values Statement	✓	100%	0 hrs	1 day?	Thu 1/22/09	Thu 1/22/09							
16	Work Breakdown Structure	✓	100%	24 hrs	3 days?	Fri 4/3/09	Thu 4/16/09							
17	Expected Results	✓	100%	136 hrs	1 day?	Fri 4/10/09	Thu 4/16/09							
18	Project Budget	✓	100%	224 hrs	28 days?	Thu 1/22/09	Thu 4/16/09							
19	Schedule of Tasks and Milestone Events	✓	100%	16 hrs	1 day?	Thu 1/22/09	Thu 1/22/09							
20	Individual Team Member Assignments	✓	100%	16 hrs	1 day?	Thu 1/22/09	Thu 1/22/09							
21	Designation of Roles	✓	100%	16 hrs	1 day?	Thu 1/22/09	Thu 1/22/09							
22	Feasibility Study	✓	100%	864 hrs	18 days?	Thu 1/15/09	Thu 2/26/09						1/16	
23	Mid-Term Review Presentation	✓	100%	128 hrs	4 days?	Thu 2/26/09	Thu 3/12/09							
24	Final Design	✓	100%	408 hrs	17 days?	Thu 3/12/09	Thu 5/14/09							
25	Final Economic Analysis	✓	100%	360 hrs	15 days?	Tue 3/3/09	Fri 4/24/09							
26	Exhibit Poster & Brochure	✓	100%	138 hrs	2.88 days	Thu 4/16/09	Sun 4/26/09							
27	Final Presentation	⊗	60%	0 hrs	6 days?	Thu 4/16/09	Thu 5/7/09							
28	<i>Final Report</i>	⊗	0%	0 hrs	6 days?	Fri 4/17/09	Fri 5/8/09							

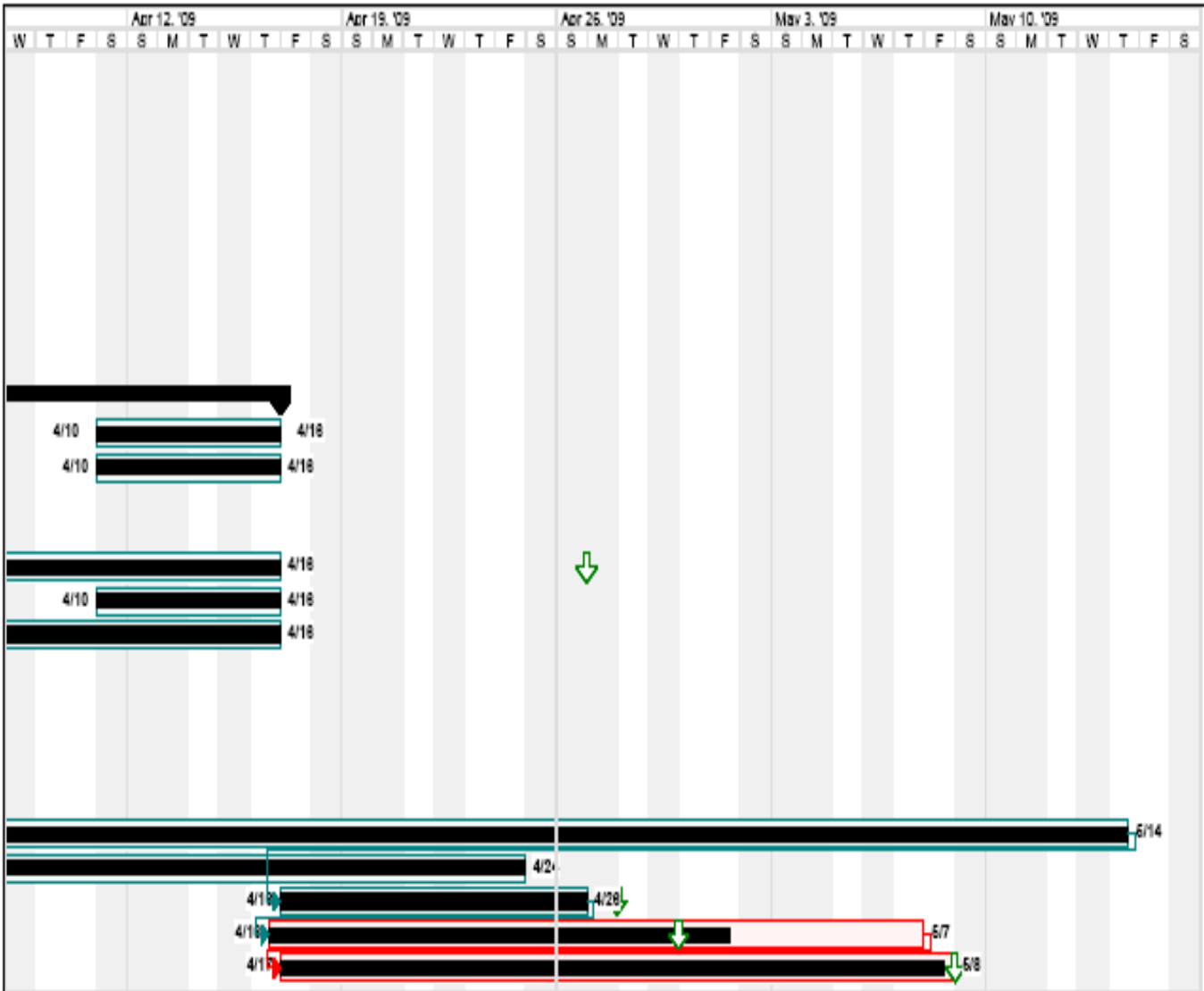
Project: Project Management IPRO 31 Date: Sun 4/25/09	Task		Rolled Up Task		External Tasks	
	Critical Task		Rolled Up Critical Task		Project Summary	
	Progress		Rolled Up Milestone		Group By Summary	
	Milestone		Rolled Up Progress		Deadline	
	Summary		Split			

Page 1



Project: Project Management IPRO 31 Date: Sun 4/26/09	Task		Rolled Up Task		External Tasks	
	Critical Task		Rolled Up Critical Task		Project Summary	
	Progress		Rolled Up Milestone		Group By Summary	
	Milestone		Rolled Up Progress		Deadline	
	Summary		Split			





Project: Project Management IPRO 31 Date: Sun 4/26/09	Task		Rolled Up Task		External Tasks	
	Critical Task		Rolled Up Critical Task		Project Summary	
	Progress		Rolled Up Milestone		Group By Summary	
	Milestone		Rolled Up Progress		Deadline	
	Summary		Split			

## Team Structure and Assignments

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Our project went through three phases of subgroups throughout the semester. The first subgroup phase was that listed in the project plan and consisted of a cost analysis team, a fuel cell analysis team, and an impurities team.

After the research collected in phase I was compiled the group decided that using a fuel cell to power an automobile was not feasible given the current technology. The focus then shifted to finding a new vehicle that could be powered by a fuel cell. The subgroups for this second phase of the project consisted of an unmanned aerial vehicle (UAV) team, an unmanned undersea vehicle (UUV) team, and a fuel cell team. The members in each team were mostly the same as in the first phase.

After the information from phase II was compiled the group decided it would be easier to implement a fuel cell power system into a UAV. The group also decided to use a PBI fuel cell rather than a PEM fuel cell. After we had decided to focus on a UAV we split into new subgroups again consisting of a fuel cell design team, a fuel system design team, and a transformers team. This time the members in each subgroup changed substantially according to the background of each individual.

We did not predict these subgroup phases, but rather they evolved from how the project was going and were an essential part to keeping the team organized and productive.

## Sub-Groups Phase I

<b>Cost Analysis</b>		
Researched the economic feasibility of commercial fuel cell		
<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Joshua Willett	Cost Analysis Team Leader	Cost of fuel cell.
Priscilla Zellarchaffer		Researched cost of gasoline as fuel source.
Samira Matezic		Researched the production cost of hydrogen from CH <sub>4</sub> .
Matthew Marks		Cost of combustion engine.
Marisol Aguirre		Researched cost of JP-5 as fuel source.
Bethany Nicholson		Researched cost of JP-8 as fuel source.
William Mocny		Researched the production cost of hydrogen from CH <sub>4</sub> .

**Fuel Analysis Team**

Researched different method of obtaining and storing Hydrogen.

<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Anam Moin Khan	Fuel Analysis Team Leader	Water Gas Shift reaction.(GWS)
Adam Smith		Researched storage and transportation of Hydrogen.
Galina Shpuntova		Preferential Oxidation
Elizabeth Corson		Catalytic Reforming, JP-5, JP-8
Kathleen Baker		Steam Methane Reforming (SMR)
Hussein Massoud		Desalination and Electrolysis for Hydrogen production

<b>Impurities Team</b>		
Researched different methods to prevent catalyst poisoning and membrane failure		
<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Ellen Kloppenborg	Impurities Team Leader	Researched membrane failure
Yin Zhao		Researched anode
Hannah Zwibelman		Researched fossil fuels
Elena Dorr		Polymer electrolyte
Steven Booher		Researched fossil fuels
Emily Kunkel		Researched catalyst
Bryce Swillum		Researched cathode
Kolade Adebowale		Researched catalyst



## Sub-Groups Phase II

<b>Unmanned Submersibles and Fuel</b>		
Researched the feasibility of using fuel cell in Unmanned Undersea Vehicles (UUV's) and found out more about the fuel		
<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Joshua Willett	UUV Team Leader	Use of Fuel inUUV's
Samira Matezic		Advantages of using fuel cells in UUV's
Matthew Marks		JP-8:Storage, cost, chemical properties, hydrogen extraction
Marisol Aguirre		Advantages of using fuel cells in UUV's
Bethany Nicholson		Disadvantages of using fuel cells in UUV's
William Mocny		Disadvantages of using fuel cells in UUV's
Kolade Adebawale		Disadvantages of using fuel cells in UUV's
Steven Booher		UUV background

**Unmanned Aerial Vehicle Team**

Researched the feasibility of using a fuel cell to power an unmanned aerial vehicle (UAV)

<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Anam Moin Khan	UAV Team Leader	Autonomy of UAV's
Adam Smith		History of UAV's
Galina Shpuntova		Existing UAV Designs
Elizabeth Corson		UAV Endurance
Kathleen Baker		Functions of UAV's
Hussein Massoud		UAV Endurance
Elena Dorr		UAV Classifications

**PBI Fuel Cell Team**

Researched the PBI fuel cell and compared it with previous research on the PEM fuel cell

<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Ellen Kloppenborg	PBI Fuel Cell Team Leader	Cell Materials: phosphoric acid, carbon backing and support layers, and bipolar plates
Yin Zhao		Fuel cell literature, discussion with experts
Hannah Zwibelman		Researched synthesis of PBI/phosphoric acid membrane
Emily Kunkel		Catalyst comparison of PEM and PBI fuel cells
Bryce Swillum		PBI fuel cell's susceptibility to impurities and poisoning
Pricilla Zellarchaffer		PBI/phosphorus acid. Cost comparison of PEM and PBI fuel cells

### Sub-Groups Phase III

<b>Fuel Cell Design Team</b>		
Designed the fuel cell system to power the selected plane.		
<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Ellen Kloppenborg	Fuel Cell Design Team Leader	Calculations of fuel cell components, mass and flow rates
Hannah Zwibelman		Researched cost of fuel cell elements and implementation of reforming process
Yin Zhao		Researched fuel cell. Computer Simulation of process
Bryce Swillum		Researched the battery and capacitor needed to start fuel cell
Joshua Willett		Researched the effectiveness of bipolar plates and insulation materials
Marisol Aguirre		Researched the use of graphite in fuel cells and different insulation materials.
William Mocny		Researched metal bipolar plates and battery for hybrid system

**Transformers Team**

Designed the power system in terms of what components would be needed to supply power to the motor and other accessories.

<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Anam Moin Khan	Transformers Team Leader	Researched motors and batteries for the different UAV models considered
Matthew Marks		Power outputs and requirements, motor specifications, batteries for hybrid system
Elena Dorr		Transformers, electricity and circuit design. Weight concerns of transformer and other electrical components
Adam Smith		Researched batteries in UAVs
Steven Booher		Fuel cell and transformer calculations
Kathleen Baker		Types of transformers
Hussein Massoud		Electrical configuration of transformers, capacitors, and battery

**Fuel System Design Team**

Designed system to store, transport, and reform the fuel.

<b>Name</b>	<b>Role</b>	<b>Concentration</b>
Galina Shpuntova	Fuel System Design Team Leader	Designed air supply system to fuel cell
Elizabeth Corson		Fuel system design using Hydrogen and then Methanol. Methanol reforming
Emily Kunkel		Designed piping from fuel tanks to reformer
Kolade Adebawale		Designed piping from fuel tanks to reformer
Priscilla Zellarchaffer		Analyzed methanol reforming and calculated the amount of hydrogen produced
Samira Matezic		Researched air supply and fan size
Bethany Nicholson		Researched hydrogen-producing reactions. Designed piping from fuel tanks to reformer.

## Team Member Contributions

**Adam Smith** – Adam was one of the IPRO group team leaders. He helped to organize the groups and communicate between individuals. He participated in the fuel analysis subgroup researching fuel storage and transportation, in the unmanned aerial vehicle group presenting the history of unmanned flight, and in the transformer team researching battery systems in existing UAVs. In addition to this he worked on the final poster for IPRO Day.

**Hannah Zwibelman** – Hannah was one of the two IPRO group team leaders. She subdivided the group into three smaller independently lead subgroups and assigned each group a set task. The three subgroups she worked in were fuel cell impurities where she researched catalyst fouling then PBI fuel cell research and application and finally fuel cell design. She served as the go to person for all three sets of subgroups to send their information to for compilation.

**Kolade Adebowale** – In the impurities subgroup Kolade researched the Platinum catalyst for the PEM fuel cell. In his second group, the UUV team, Kolade looked for disadvantages of using fuel cells in UUV's. Lastly, Kolade was a member of the fuel system design team where he helped to design the piping system to transport the methanol to the reformer.

**Marisol Aguirre** - Marisol Aguirre researched the cost of JP-5 as a member of the cost analysis team. Then she looked for advantages of using fuel cells to power UUV's. Finally, as a member of fuel cell design team she researched the use of graphite in fuel cells and different types of insulation materials that would be most suitable for the fuel cell.

**Kathleen Baker** – Kate started out researching within the Fuel Analysis group gathering information about Water Gas Shift Reactions and Steam Reforming. From this group, she moved onto the functions of unmanned air vehicles (UAVs). Once UAVs were settled upon as the final topic of research, Kate researched the different types of reformers.

**Steven Booher** – Steven's first group, the impurities team, Steven researched fossil fuels. Then as a member of the UUV team he looked into the background of UUV's and their uses. In his last group, the transformers team, he helped with the calculations for the fuel cells and the transformers. In addition to all this, Steven designed the logo for our IPRO and worked on the poster for IPRO day.

**Elizabeth Corson** - In her first subgroup Elizabeth researched the different types of fuels that would produce Hydrogen and the process involved. (catalytic reforming, JP-5, JP-8, storing Hydrogen, ,ect). In her second subgroup she researched various types of unmanned aircrafts (UAVs) in an effort to determine if they were likely to be compatible with fuel cell power. In her third subgroup she researched the actual design of a fuel system for a vehicle, first with Hydrogen as the fuel, then with methane.

**Elena Dorr** – Elena conducted research, took notes, analyzed and created reports on the following: PEM Fuel Cells, vehicles powered by PEM fuel cells, electrolytes, impurities and their effects on performance, unmanned aircraft (general and classification),

transformers, toy airplanes, electricity and circuit design. She also analyzed various aircraft and weight concerns surrounding transformers and other electrical components needed.

**Anam Moin Khan** – In fuel analysis Anam researched the water gas shift and other techniques of producing fuel for the fuel cell engine. After that she was a part of the UAV group. They researched the reasons and benefits of using a fuel cell engine in UAV's, she researched the autonomy of the UAV and the future prospects that were being researched. The main goal was to see if we could use fuel cells in UAV's, come with logical reasoning as to why we should research more into the topic. She was the group leader for the electronic and hybrid group. Her role was to assign different research tasks to the group members. They researched the different motors, transformers, inverters and reusable batteries that could be used. After gathering all the research from everyone, Matthew and Anam would discuss what would suit the project the best and then convey the information to the other groups. Her roles including getting the group together and finishing their tasks by the given time period, making sure everyone knew what they were doing, as well as researching motors and batteries and acting as a liaison with the other groups.

**Ellen Kloppenborg** – Ellen was the team leader for the impurities subgroup. In this group, they divided out the parts of a PEM fuel cell and each researched the impurities that affected that particular portion. Ellen was responsible for finding information on the membrane. For the next set of subgroups, she was team leader of the group focused on the PBI fuel cell. Like before, they divided up the fuel cell into parts and each researched the particular component. She looked into many of the materials used in the cell including: phosphoric acid, carbon backing and support layers, and bipolar plates. She continued to be involved in the fuel cell group as the semester progressed, working on the calculations of the components necessary for the fuel cell, including masses and flow rates. In addition, Ellen researched possible planes that could be used by the team and helped to coordinate the rest of the group.

**Emily Kunkel** – Emily's first group was the impurities subgroup. She was responsible for finding out more about the Platinum catalyst for the PEM fuel cell. For her second group, Emily worked with the fuel cell team and compared the PEM and PBI fuel cells in terms of the catalyst. Finally, she was part of the fuel system design team where she helped design the piping system to transport the methanol to the reformer.

**Matthew Marks** – In the cost subgroup, Matt determined the cost of an internal combustion engine, in order to compare with a fuel cell engine. In the next subgroup (UAV's vs. unmanned submersibles), he researched the storage information, cost, chemical properties, and hydrogen extraction from JP-8. In the transformers subgroup, he compared power outputs from fuel cell to power requirements for motors, on the different sizes of planes we were looking at. Matt then found specifications for the motor to be used in the 2-man Cessna plane currently being worked on. He also helped look at batteries to power the plane while the fuel cell engine is warming up.



**Hussein Massoud** – In his first group, Fuel Analysis, Hussein was assigned the task of researching the feasibility of obtaining hydrogen from water through electrolysis. In his second group, UAV Team, he helped his teammates choose the type of airplane/motor we would be working on. For his last group, the transformers team, Hussein worked with the group to figure out the electrical configurations (transformers/capacitors/batteries) that would be needed to fly the plane.

**Samira Matezic** – For the cost analysis team, Samira researched the production cost of hydrogen from CH<sub>4</sub>. In the second group, UUV, she researched the advantages of using fuel cells in UUV's. For the third group, fuel system design, she researched air supply, in which she determined the fan size.

**William Mocny** - Was placed in the cost subgroup at outset of the semester and researched the cost effectiveness of methane and a reformer for use in a fuel cell system. His second group was that of the unmanned submersible, and his job was to study the disadvantages of using a fuel cell on a submersible and if they outweighed the advantages. Finally, Bill was placed on the actual fuel cell group for the UAV design and researched metal bipolar plates for use in the fuel cell as opposed to graphite, as well as finding a suitable battery that could power the plane and other devices before the fuel cell could warm up.

**Bethany Nicholson** – As a member of the cost analysis team, Bethany researched the cost and chemical properties of JP-8 jet fuel. In her second group, which was the UUV group, she researched some of the disadvantages of using fuel cells in a UUV. Lastly, Bethany was in the fuel system design group where she researched different reactions that could be used to produce hydrogen as well as helped to design the piping system that transports the fuel (methanol) to the reformer. In addition to this she worked on the Team Structure and Assignments section of the final report.

**Galina Shpuntova** - Initially, as part of the group researching background, Galina looked into existing solutions and technologies by looking at technical literature. She was also responsible for compiling the background section for integration into the overall report. Then she was a part of the group researching the possible unmanned aircraft application of the fuel cell technology, specifically researching existing aircraft models. This flowed logically into her putting a lot of work into finding UAV models that we could use for our project. She was then group leader for the fuel transport and reforming group, which focused on supplying the fuel cell with the correct flowrates of air and hydrogen, as well as fuel tank design. Galina also designed the piping and selected the blower necessary to supply the fuel cell with oxygen.

**Bryce Swillum** - Bryce was originally a member of the impurities team where he researched the impurities and poisoning that can occur at the cathode or a PEM fuel cell. He also researched the impurities and poisoning that a PBI fuel cell is susceptible to while on the PBI fuel cell team. Bryce's third subgroup was the fuel cell design team where he researched the battery and capacitor that would be needed upon start up for the fuel cell.

**Joshua Willett** – The beginning of the project led to Josh becoming the leader of the cost analysis group. In that leadership role he oversaw the research of the cost benefit or deficit of developing fuel cells for automotive applications. After the decision that automotive applications were not cost effective he led the unmanned underwater vehicles (UUV) research team to determine the effectiveness of fuel cells in underwater vehicles. The next phase of the project gave Josh the opportunity to work on the fuel cell research group under Ellen, he researched different bi-polar plates to determine the most effective one to use. He also researched different insulation materials for use in the fuel cell.

**Priscilla Zellarchaffer** – Priscilla participated in several groups, she performed cost analysis on available fuels as a possible fuel source, analyzed cost synthesis of PBI/phosphorus acid, performed cost comparisons on PEM and PBI fuel cells, as well as analyzed methanol reforming and calculated the amount of hydrogen that can be derived from methanol. She performed a detailed breakdown of each member of the team and tracked progress of our project using project manager (Gantt chart). She also helped with the poster and brochure for the project.

**Yin Zhao** - Yin Zhao is a senior chemical engineering student in the IPRO. As such, he was an integral part of the fuel cell design team. Alongside other seniors, Yin conducted literature research, surveyed available resources through internet and held discussions with experts. He helped to design the fuel cell stack and performed a computer simulation for the process, along with other team oriented functions.

## Budget

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<b>ITEMS</b>	<b>UNIT PRICE</b>	<b>QTY</b>	<b>PRICE</b>	<b>PURPOSE</b>
Food & Beverages	\$20	25	\$400	Food and beverages for occasional meetings
I PRO Day	\$100	1	\$100	Poster printing and set up materials
<b><i>TOTAL:</i></b>			<b>\$500.00</b>	

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# Code of Ethics

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The team followed the principles described by June Ferrill in the book *The Seven Layers of Integrity*. In the evaluation of fuel cells and investigation into fuel cell design and applications, the IPRO team constantly made safety a priority, as it is the single most important element for those looking at a new energy technology.

Overarching standard: The IPRO team shall hold the safety, and welfare of potential fuel cell users as well as the environment to the highest regard.

## Seven Canons

1. Law: The IPRO team shall follow the law.
  - a. Pressure:
    - i. Design a fuel cell that meets desired specifications.
    - ii. Design the fuel cell in a short amount of time—race to create a working design.
  - b. Risks:
    - i. Use information from companies or institutions currently producing fuel cells and unmanned aircraft designs without their approval—against the law!
2. Contracts: Adhere to intellectual property agreements
  - a. Pressure:
    - i. Successful IPRO
  - b. Risks
    - i. Stealing other group member's ideas—weakens team
    - ii. Stealing other IPRO's ideas—cheating
3. Professional Codes: The IPRO team will work together, and listen to each other's ideas
  - a. Pressure:
    - i. Perform well within the team
  - b. Risks:
    - i. Not listening to other members—weakens team relations
    - ii. Not working together—missing valuable ideas and information
4. Industry Standards: Doesn't exceed areas of competence and seeks continuous improvement.
  - a. Pressure:
    - i. Create working fuel cell
  - b. Risks:
    - i. Not striving for new ideas—halting progress
    - ii. Exceeding areas of competence—creating unsafe design.
5. Community: Keep the communality in mind while designing alternative energy.
  - a. Pressure:
    - i. Design a fuel cell in a short amount of time
  - b. Risks:
    - i. Overlook safety, potentially injure someone with unsafe design
    - ii. Overlook environment, potentially emit toxins or harm the environment
6. Personal Relations: Work together toward a common goal

- a. Pressure:
    - i. Create the strong IPRO Team
  - b. Risks
    - i. Not being inclusive—missing out on possible talent
    - ii. Choosing team members in an unethical way—weakens team
7. Moral Values: Follow what you know is right, lead by example
- a. Pressure:
    - i. Culture of group
  - b. Risk:
    - i. Not challenging the group when there are disagreements—group think
    - ii. Unequal share of work—weakens team progress and relationships.

## Results

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Much literature was read in order to find information about PEM fuel cells, airplanes, and their corresponding components. References can be found in the [works cited section](#) of the report.

The team first looked at PEM fuel cells based on Nafion, the impurities that could interfere with their performance, and their application to automobiles. Membranes in the PEM fuel cell are typically made of sulfonated perfluorinated polyethers, such as Nafion 117, Flemion, or Aciplex. (“New”). Due to the structure of these polymers, the biggest issue regarding this part of the fuel cell is water management. The membrane must be kept wet enough so that proton transfer can occur, but that flooding will not. If the membrane is allowed to dry, it could lead to holes and cracks (Ramani) or even cause the catalyst to separate from the membrane (Okada). Due to this, PEM fuel cells are typically operated below 100 °C, so that the humidification may be maintained, often a temperature of 80 °C is used to make sure that the membrane does not dry out (“Proton”), although higher temperatures can be achieved through the use of higher pressures (Hektor). Unfortunately, operating at lower temperatures leads to less proton conductivity.

The electrolytes within the membrane carry electrically charged particles from one electrode to another<sup>3</sup>. The electrolyte plays a key role; it must permit only the appropriate positively charged ions to pass between the anode and cathode, but not electrons. If free electrons or other substances could travel through the electrolyte, they would disrupt the chemical reaction.<sup>1</sup>

One advantage of the PEM, as compared to many other types of membranes, is its low weight and volume. It looks similar to plastic wrap, and is only 20-30 microns thick.<sup>4</sup> Efficiency of a PEM fuel cell is about 40-50 percent and the operating temperature is about 80 °C (~175 °F), and the power output generally ranges from 50 to 250 kW. This also allows for less warm-up time as well as less wear and tear on system components.<sup>1</sup> However, they require climate control in harsh environments to maintain the integrity of the membrane.<sup>3</sup> Seal temperature and durability are two other concerns. The durability of the membrane is jeopardized when it is continuously heated up and then cooled back down to room temperature after use. The solid, flexible electrolyte will typically not leak or crack; however, the fuel used for it must be purified.<sup>1</sup>

The difficulty in meeting specific operating conditions stems from the decrease in water content of the polymer electrolytes in the desired temperature range; replacement of water while retaining conductivity is a problem, as the membrane must be hydrated in order to function and remain stable, and can be compromised without a high pressure hydration system. The need to operate at these temperatures and at low relative humidity is the primary challenge for PEM fuel cells. Researchers at Georgia tech have been adding the chemical triazole to membranes to increase conductivity and reduce moisture dependence. In addition to improving conductivity, replacing the water in membranes with triazole increases operating temperature from 80 °C to 120 °C, above the boiling point of water, thus permitting elimination of the water management system. This higher operating temperature allows for less purity in the hydrogen fuel since it is less sensitive to CO poisoning.<sup>4</sup>

Impurities can also affect membrane performance. Metal ions such as iron, sodium, calcium, and magnesium (“Method” and Garzon) are introduced into the system from metal plates in the fuel

cell or contaminants in the fuel (“Proton”). These ions bond more strongly to the membrane than protons do, lowering the amount of proton transfer taking place. Additionally, the metal ions have different hydrated states than the hydrogen ions, which lower the water content of the cell and thereby limit the ionic conductivity of the membrane (“Method”). The membrane can shrink due to the cross-linking of polymer chains with cations (Okada). Desulfonation of the polymer and degradation by oxygen radicals caused by the hydrogen peroxide formed at the oxygen reduction electrode can cause degradation of the membrane as well (Ramani).

Unmanned Underwater Vehicle (UUV) and Unmanned Air Vehicle (UAV) applications were investigated in order to determine which would be most applicable to fuel cell power.

The history of UAV’s begins with the desire to use unmanned aircrafts in wartime. On August 22, 1849, the Austrians attacked Venice with balloons full of explosives. About half the balloons that worked dropped their payload over the city, while the other half were blown back over the Austrians due to changing wind currents.

More recently, A. M. Low started developing radio-controlled aircraft in the British Air Corps in 1916. This was the first time that the user maintained some control over the aircraft. Low’s aircraft was more like a missile, with slight control over direction while the speed remained out of his control. After World War I, companies started using gyroscopes to enhance their aircraft.

In the 1930s’ the United States Army became interested in the use of unmanned aircraft. Reginald Denny began a model shop and eventually developed planes for military use. After four tries, he found one they were interested in and won a contract in 1940. After World War II, the need for faster drones became evident and UAV’s with the capability of models such as the Mach 2 were developed. Most recently, a drone intended for weather observation and measurement of the atmosphere became the first unmanned aircraft to cross the Atlantic.

UAV’s can be placed into several categories. They can be categorized by functions such as range, altitude, weight, wing loading and engine type or by mission or purpose.

The ‘Tier’ system is used for integration between aircraft and support personnel on the ground. Different systems are to be designed for the different branches of the armed forces. They range in cost from a few thousand dollars to tens of millions of dollars with aircraft ranging from less than one pound to over 40,000 pounds. Examples include long altitude and long endurance, medium altitude and medium endurance, high altitude and 24-hour time-on-station capability, high altitude and long endurance low observable. Future Combat Systems is the military’s principal modernization scheme; however, most UAV projects for this have been canceled, except for small units and brigades.

Most military applications of unmanned flight involve surveillance. There are two UAV’s that the US military uses: the RQ-4 Global Hawk and the MQ-1 Predator. The Global Hawk is used for surveillance and is jet powered which might make it more difficult to adapt to a fuel cell energy source. The Predator is also a surveillance plane but unlike the Global Hawk, it carries two Hellfire missiles as well. Other functions include search and rescue, and data collection.

In the initial stages of development, UAV's were very much similar to remote controlled model aircraft. The aircraft would have on board electronics to send information to the base, where a team would be monitoring and manipulating the actions of the UAV. Since the 1980's, research started concentrating on making the UAV's more autonomous. The research and development in this field is still in its infant stage. Doug Davis, director of the FAA's unmanned aircraft program office believes, "that the capabilities we're talking about will be available for 'file and fly' sometime between 2020 and 2025."

Both the military and the private sector have been involved in the development of such machines without restriction, but a license is required to carry out such research. As of now, research is being done in the areas of sensor fusion, communication, path planning, motion planning, regulation and task scheduling. The goal is for UAV's to be autonomous enough that when they receive data from different sensors and functions, they are able to manipulate the data and figure out a course of action without being directed by the base camp or monitoring base. More recently, research has started using a hierarchical control system in order to program and develop behavior generation, sensory perception, value update and world model.

- *Behavior generation* is responsible for executing tasks received from the superior, parent node. It also plans for, and issues tasks to, the subordinate nodes.
- *Sensory perception* is responsible for receiving sensations from the subordinate nodes, then grouping, filtering, and otherwise processing them into higher-level abstractions that update the local state and which form sensations that are sent to the superior node.
- *Value judgment* is responsible for evaluating the updated situation and evaluating alternative plans.
- *World model* is the local state that provides a model for the controlled system, controlled process, or environment at the abstraction level of the subordinate nodes.

Synthetic vision has also been experimented with as it provides situation awareness to the operators by using terrain, obstacle, geo-political, hydrological and other databases. A typical SVS application uses a set of databases stored on board the aircraft, an image generator computer, and a display. Navigation solution is obtained through the use of GPS and Reference Systems. Developments are being done in the field of Artificial Intelligence and Controlled Systems and Sciences to use the technology what was once used for AI robots to be used in UAV's. QinetiQ, a Britain-based company, and Boeing have started a partnership to explore the possibilities.

One of the more important aspects of a UAV is the amount of time it can remain in the air, or its endurance. The maximum flight time ever recorded was 96 hours of continuous flight. The eventual goal would be for a 5 year life time. Airtime is limited by fuel, so the lighter and more efficient the fuel, the greater amount of time the UAV can remain in the air. In terms of altitude endurance, UAV's have flown up to 100,000 feet. There are different designs based on low-, medium-, and high-altitude, which should be decided upon based on the purpose of the UAV. Maximum speed is variable depending on the size of the payload. Boeing has already experimented with hydrogen fuel cells on small airplanes to test their efficiency and durability as an alternative to batteries and internal combustion engines. There is ongoing research of fuel cell powered UAV's, with many different design ideas available.



Many of the advantages of using fuel cells in UAV's would also be advantageous for use in military submersibles: no noise, no exhaust, minimum waste heat transfer to ambient seawater, no power limits, no diving depth restrictions, modular design of the entire propulsion system, and low maintenance requirements. Fuel cells give UUV's a higher performance due to its composite cylinders. A buoyancy compensation results from this and the use of a hydrogen tank. Carbon nano-fibers are ideal for the pressure vessels. Fuel cells are suitable for integration into basically any conventional submarine as a plug-in solution or in a new submarine.

For example, the 28-foot-long Seahorse, specially built for blue-water mine sweeping, can traverse 300 nautical miles on batteries that will keep it going for up to 72 hours. Fuel cells could be an advantageous substitution for these batteries. Another example is the U212 submarines, currently made in Germany, consisting of nine PEM fuel cells, providing between 30kW and 50kW each. For higher speeds, connections are made to the high-performance lead acid batteries. An MTU 16V-396 diesel engine powers the generator from Piller GmbH for charging the battery installed on the lower of the two decks at the forward section of the submarine.

There are also many obstacles in trying to place a fuel cell stack in an unmanned submersible; the first is harnessing a fuel source. If hydrogen is used, the problem becomes how to store large volume container of hydrogen compressed on board. The tank takes up the needed space and power away from the submersible, because of the need to compress both the hydrogen and oxygen since oxygen is not easily accessible from the air as it would be in other applications. This method can also be dangerous. The second solution is to cryogenically freeze the hydrogen into a liquid, but once again, a considerable amount of energy is consumed and such a method is impractical under sea level. This means that the hydrogen must then be obtained from a different fuel source such as methane, JP-5, or JP-8 although it adds more weight to the submersible.

UAV applications had been chosen due to the readily available supply of oxygen. Once the application was selected, much work was done in order to select a proper plane for the project, including research on unmanned, model, and one or two-seater aircraft.

It is difficult to discuss all models of UAV's currently available, largely because there are so many. Most designs are coming from mainstream manufactures like Boeing, Lockheed Martin, and Northrop Grumman, as well as less-known ones including Aerovironment (AV), General Atomics (GA), AAI, Aurora Flight Sciences and Advanced Ceramics Research. AV and GA have about five models apiece and are widely used by the United States military, as well as by research groups and companies in asset management. A few models that stand out are the AV WASP III, which is the lightest, weighing in at less than 300 grams (smaller than many model airplanes!) and the large and deadly General Atomics MQ-9 Reaper, which can carry up to 14 500-pound Hellfire missiles, which alone weigh several thousand pounds!

Several models of UAV's were considered for fuel cell integration. Initially, a revolutionary Micro Air Vehicle utilizing active flow control was selected, designed by a team from the IIT Mechanical, Materials, and Aerospace Engineering department for their final project and nicknamed the "Screech Owl. This option offered complete and reliable information on the vehicle's specifications. Screech Owl required 100 Watts of energy for an hour, provided at 5-20

V. The power system needed to fit into 130 grams and a space 10x5x1 cm. This was determined to not be feasible with a fuel cell system.

Subsequently, commercial models were considered, but insufficient data on their power systems was readily available to draw any conclusions. Furthermore, certain systems that appeared likely candidates were already equipped with fuel cell power systems (for example, the Puma craft by Aerovironment).

To acquire better information on the nature of the aircraft, model airplanes were considered. Radio controlled model airplanes are available in a range of sizes that are close to UAV sizes, but they do not feature the sophisticated (and often classified) control technology necessary for an autonomous reconnaissance system. One of the more successful options was the Hangar 9 ¼-scale model of the Cub J-3. The airplane weighs approximately 15 pounds, and the recommended setup requires battery that provides 74 W at 11.1 V for an hour. The Lithium-polymer (LiPo) battery is 3.4x4.6x1.6 cm. This aircraft yielded better results than the Screech Owl, but still lacked the space and lift necessary to carry the power electronics required for the fuel cell to provide the proper voltage, current, and power.

Extrapolating from previous results, it was found that a larger vehicle would be more practical for a fuel cell application. Therefore, the decision was made to transform a Cessna Skycatcher aircraft to a UAV by placing the fuel cell into the cockpit area. The Cessna weighs 1320 lb, and the cockpit area is 46.8x44x69 in. This proved sufficient to provide the necessary 100kW, although some other challenges were encountered.

Various fuel systems exist to fulfill the needs of the variety of UAV. Smaller ones tend to carry batteries while the larger ones require an alternating (internal combustion) engine. Internal combustion engine aircraft's endurance depends strongly on the percentage of fuel burned as a fraction of the total weight, making it largely independent of aircraft size; however, in-flight UAV refueling capabilities are not yet available, and it is still a limiting factor. Such technology may be available by 2010. As an alternative, solar-electric UAV's hold a high potential for unlimited flight, although the record flight time as of July 2008 is 82 hours and 37 minutes. DARPA is in the process of signing a contract to building a UAV, which should have an enormous endurance capability (continuous flight, no maintenance) of about 5 years.

PBI fuel cells were also studied in great depth. Impurities, materials of construction, operating temperatures, and other aspects were researched in order to provide a good design basis.

Polybenzimidazoles were developed by the US Airforce Materials Lab in conjunction with Dupont and Celanese Research Company in the 1960's. Early applications were found in thermally stable and nonflammable textiles (firefighter's overcoats, astronaut space suits and metal workers gloves), high temperature matrix resins, adhesives, and foams. PBI polymer is synthesized in well-developed multi-step process; 3, 3', 4, 4'-tetraaminobiphenyl and diphenyl isothalate are combined in a two-step melt/solid polymerization process that produces PBI powder, phenol and water. The polymer is then dissolved under high pressure conditions in DMAc/LiCl, filtered, dried and spun into fibers, which are then washed, dried, and for use in fuel cells, treated with phosphoric acid. Phosphoric acid is used to dope the PBI membrane before it is put into the cell. A bath of 80 wt%

acid has been used to reach a level of 6.5 molecules per polymer repeating unit (Lobato). Another study showed that at a level of 5.7 moles of phosphoric acid, the conductivity was  $4.6 \times 10^{-3} \text{ S}\cdot\text{cm}^{-1}$  at room temperature,  $4.8 \times 10^{-2} \text{ S}\cdot\text{cm}^{-1}$  at  $170^\circ\text{C}$ , and  $7.9 \times 10^{-3} \text{ S}\cdot\text{cm}^{-1}$  at  $200^\circ\text{C}$ . Activation energies were 17 – 25 kJ/mol for acid doping between 2.0 and 5.6 moles of phosphoric acid per repeating unit, which is close to 85 – 93 weight percent solutions of phosphoric acid (Li).

Phosphoric acid was first considered for use in fuel cells due to its higher boiling point than water and similar electrolytic properties (English). Its use comes with both positives and negatives, depending on the portion of the cell it affects. Ionic conductivity and power generation efficiency increase with increasing amounts of this acid in solid electrolytes. In the catalyst layer, however, the phosphoric acid can lessen catalyst performance by adhering to platinum, decreasing the surface area and therefore lowering the efficiency of the cell (“New”). Overall, less cooling is required when phosphoric acid is used as opposed to water, and humidification is not needed (English). Carbon monoxide poisoning is less of a problem in the PBI/phosphoric acid cell than for PEM fuel cells, since at  $200^\circ\text{C}$ , 1 percent CO with a current density of  $1.3 \text{ A}\cdot\text{cm}^{-2}$  and 3 percent CO with current density of  $0.8 \text{ A}\cdot\text{cm}^{-2}$  in hydrogen produce less than 10 mV of cell voltage. This means that reformed hydrogen can be used directly from a methanol reformer (typically at temperatures of  $180$  to  $250^\circ\text{C}$ ) without going through additional cleanup (Li).

A major problem with the use of phosphoric acid is the leaching of the acid from the cell that occurs. Cells need to be kept at  $160^\circ\text{C}$ , or the exhaust steam may turn to water and carry acid out of the cell. Currently, temperatures cannot be maintained in automotive vehicles due to the various conditions related to driving, such as: idling, going through traffic, and driving at full-speed. It also can take a long time to reach this operating temperature, resulting in inefficient cells. There has been work done to reduce this leakage. VW has developed a coating on the electrodes that prevents the acid from leaking, but there is still about six percent loss after 1,000 hours (English).

The materials used for the electrolyte, anode, and cathode should have a combined area-specific resistance below  $0.5\text{V}/\text{cm}$ , preferably around  $0.1 \text{ V}/\text{cm}$  in order to have high power density (1 kW/kg is desired for transportation). This will reduce costs, lowering the amount of material necessary to generate a certain amount of power (Steele).

Backing and support layers are needed within the cell to ensure good bonding and allow for the supply of reactants and the removal of water. Backing layers are often made of carbon fiber paper or cloth. In one study, this paper was wet-proofed using immersion in a 20 percent polytetrafluoroethylene (PTFE) solution and baking at  $360^\circ\text{C}$  for 30 minutes to polymerize the PTFE. The wet-proofing led to a greater porosity for the electrode and improved the bonding between the carbon support and the carbon paper.

Research is being done to develop the best material for bipolar plates, which serve as flow fields and current collectors. Graphite is often used, due to its resistance to corrosion, but the conductivity is lower than that of a metal. Costs for graphite plates are high, due to the channels that need to be made and the binder or resin that has to be added to make the plates impermeable because of their porosity. As a solution to this, polymers such as polypropylene can be added to graphite, since they can be made more easily and cheaply using methods like injection molding and hot pressing. Typically, carbon makes up between 50 and 80 weight percent of the mix in

order to obtain the desired conductivity while still maintaining the strength and flexibility. Metals are also an option being investigated for use in the plates; however, due to the acidic nature of the cell, many metals are not corrosion resistant enough for this application. Stainless steels are the most promising, as other choices (titanium, niobium, tantalum, and gold) are too expensive. In the cell, they are protected by a passive layer on the cathode side, but become contaminated by corrosion at the anode. Performance is satisfactory for several thousand hours, and flow channels are easily created by pressing (Steele).

To put the parts of the one of the fuel cells studied together, several different techniques have been used. To make the membrane electrode assembly in one study, the membrane was put between the two electrodes, and hot pressed at 150 °C and 100 kg/cm<sup>2</sup> for seven minutes (Lobato). In another, the hot pressing was done at 130 °C for 25 minutes with a pressure of 25 kg/cm<sup>2</sup> (Seland). VW has another method of assembly, which is done by hand. It puts its fuel cells together by putting membrane between two coated carbon tiles and then sealing this between compressed carbon plates with etched surfaces for hydrogen and oxygen flow. Hydraulic presses apply 180 psi to the stack, and then bolting occurs (English).

Research is being done to integrate parts of the fuel cell stack (including the flow field, gas diffusion layer, current collectors, electrodes, and membrane electrode assembly) into one piece using microelectromechanical systems in order to reduce size and mass. For one integrated system using a PBI fuel cell, deep reactive ion etching (DRIE) was used on a silicon wafer to form the flow field, gas diffusion layer, and current collector electrode. The flow field channels had depths and widths of 400 µm and were created so that the pressure drop from inlet to outlet was constant. Arrays of micropores (4 µm diameter by 80 µm depth) in the silicon connected the bottom of the flow field channels to the electrode layer, making up the gas diffusion layer. The electrode area for the cell was five square centimeters, and the attachment of the membrane electrode assembly to the electrode layer has been a limiting factor for PBI cells. For such a system, reformat feed to the fuel cell was provided at 190 mL/min. Airflow to the cathode was at 900 sccm (Morse)

Advantages of using PBI/phosphoric acid membranes in PEM fuel cells are: a higher operating temperature, which reduces or eliminates humidification requirements, lowers fuel reforming costs, improves electrode kinetics, creates higher ionic conductivity, smaller required heat exchanger or radiator, nearly zero water drag coefficient, and low gas permeability. Additionally, it is produced by a manufacturing process that is already well developed. Disadvantages of a PBI/phosphoric acid membrane include low molecular weights, low phosphoric acid loading, phosphoric acid retention (the acid is washed out by liquid water- the fuel cell cannot be run at room temperature), and membrane durability. Wainwright was the first to suggest the use of an m-PBI/PA membrane for use in fuel cells. A series of experiments showed that m-PBI doped with ~5 moles PA/PRU could retain conductivity at high temperature, 0.025 S cm<sup>-1</sup> at 150 °C and function in a fuel cell with a permeability of 15x10<sup>-16</sup> m<sup>3</sup>\*(STP)\*m/m<sup>2</sup>\* s\*Pa and a methanol crossover current of ~10 mA/cm<sup>2</sup>. Samms et al. followed these experiments showing that the m-PBI/PA complex was stable for temperatures up to 600 °C. Further characterization of proton conductivity across the membrane gave a range of 0.04-0.08 S cm<sup>-1</sup> at 150 °C. Performance of the cell was analyzed and a polarization curve produced by Wainwright showing a voltage of ~0.45 V at a current density of 0.20 A/cm<sup>2</sup> of a methanol based cell. Wang et al. reported a voltage of up to ~0.6 V at the same current density using a humidified hydrogen/oxygen cell. They were also able

to show that this cell operated stably at 150 °C for 200 hours. More research is being done to improve cell performance, mostly focused on increasing the amount of phosphoric acid imbibed in the membrane.

Based on the research done, the team worked to develop a PBI fuel cell system design for a Cessna Skycatcher, which was originally a two-passenger aircraft. The power required by the motor, pump, and airplane systems was found to be a total of approximately 150 kW, with the motor selected—the DMI 180B motor from ABB Drives and Motors—requiring 100 kW with a voltage of 750 V and current of 135 A. This would give a shaft speed of 2800 rpm. The fuel cell was designed around this power basis. The cockpit dimensions were set to be the maximum size for the membrane electrode assembly (MEA), but it was found that the stacking did not require the entire area. Maximum power was found by stacking the cells in blocks with total areas of 280 cm<sup>2</sup> and effective areas of 247 cm<sup>2</sup> (when a centimeter was removed from each side for assembly purposes), and 2530 MEAs stacked within this area provided the needed power. Each MEA had a thickness of 0.2 mm, with 0.1 mm from the catalyst section and 0.1 mm thick bipolar metal plates. This yielded a volume of 6249 cm<sup>3</sup>, easily fitting within the approximately 2.35 m<sup>3</sup> volume for the cockpit. The cell voltage was taken to be 0.6 V/MEA, yielding an overall voltage of 1518 V, more than what was needed by the engine. The current density was taken to be 0.4 A/cm<sup>2</sup>, which resulted in a current output of 98.8 A, lower than the amount required by the engine.

Fuel calculations were done based on a Faraday's law determination of the mass of hydrogen needed, as shown below:

$$m = \frac{QM}{Fz}$$

where Q represents the total charge, M is the molar mass, F is Faraday's constant, z is the electrons transferred for each ion, and m is the mass involved. The charge was calculated from the current delivered by the fuel cell and the desired four hours of operation time. The number of electrons participating in the reaction is two, as shown by the fuel cell reaction previously described. These calculations lead to a mass of 37.61 kg of hydrogen necessary for the reaction.

The reaction was simulated in HYSYS to get the remaining flow rates, with ten kg/h of hydrogen added to account for imperfect reaction. This led to a mass flow rate of 10.04 kg/h and a volumetric flow rate for hydrogen of 0.34 m<sup>3</sup>/h. Hydrogen used in this reaction was at 10,000 psi, as would come from a compressed tank. The flow rate of oxygen was calculated by stoichiometric proportions, coming out to 79.83 kg/h and 157.20 m<sup>3</sup>/h. Oxygen was taken to make up 21% of air by volume, so the air stream could be calculated next. This resulted in values of 342.60 kg/h and 748.30 m<sup>3</sup>/h.

Material amounts needed for the fuel cell were also calculated, based on a literature survey. For the catalyst layer, the anode required 0.4 mg of platinum per square centimeter, and the cathode required 0.6 mg/cm<sup>2</sup>. This led to amounts of 0.25 and 0.38 kg respectively for all of the MEAs combined. Carbon fiber serves as the backing and support layer for the fuel cell, and amounts required were equal to the amount of catalyst. PBI specifications were 0.36 mg/cm<sup>2</sup> for the anode and 0.6 mg/cm<sup>2</sup> for the cathode, or 0.23 and 0.38 kg total for the MEAs. Metal bipolar plates were used, because of their lighter weight, though their high corrosion rate allows them to only be used for approximately 2,000 hours. The plates chosen for the cell were stainless steel-nitrided ones,

which yielded volume of 16.47 cm<sup>3</sup> when the material space needed for the channels in the plate had been removed. Weight came out to 222.31 kg based on a density of 8 g/cm<sup>3</sup>.

A fan to bring the air into the fuel cell was also investigated. This fan would need to operate at a rate less than 0.85 m<sup>3</sup>/s and would only weigh approximately 60 grams.

These weights led to a total system weight of 271.48 kg. The motor chosen weighs 331 kg and can support up to 227 kg, so this is not a feasible system.

System costs were calculated as well. Platinum costs \$39,800/kg, so total costs for the cell come out to \$24,875. Carbon fiber paper is \$3/kg, or \$1.88 for our system. PBI costs could not be found exactly, but were estimated using a tenth of the cost of Nafion (\$600/m<sup>2</sup>). By this estimation, the cell membrane would cost \$181.82. The stainless steel bipolar plates can be found for \$5/kW, or \$750. Fan price would be approximately \$15, and hydrogen can be obtained for \$750. This leads to an overall system cost of \$26,574.

Based on the efficiency of the process, the heat generated by the cell could be found. Ideally, the cell would generate 1.11 V/MEA, but since it only will generate 0.6, it has a 54% efficiency. Total energy for the fuel cell was found using HYSYS to be 1,212,202 kJ/h, with 557,613 kJ/h being released as heat. The possibility of water cooling was eliminated due to the sheer volume of water that would be needed for this process and the extra weight this would involve. Air cooling was also researched, but the area necessary for this was found to be 418 km<sup>2</sup>, based on a heat transfer coefficient of 14 W/m<sup>2</sup> K and a log-mean temperature difference of 338.58 K (derived from a cell operation temperature of 160 °C and a wing temperature of -14 °C). The heat dissipation problem could not be solved by this IPRO team.

In the course of this project, the team also investigated the possibility of on-board reforming of methanol, since it is easier to manipulate than compressed hydrogen. The energy needed by the reformer doubled the design energy of the cell to 300 kW. Carrying methanol and water added much weight to the plane, and resulted in a total weight of 2657 kg, which was prohibitive. A reforming reactor and pump were needed for this system, and were cost was determined by Icarus. The reactor was \$92,500, and the pump was \$18,700. A maximum value for reforming catalyst cost (\$840.50) was found by summing reactant prices as found on Sigma Aldrich, as shown in the chart below.

<u>Component</u>	<u>Quantity</u>	<u>\$</u>
Cu(NO <sub>3</sub> ) <sub>2</sub>	6 kg	266
(Zn(NO <sub>3</sub> ) <sub>2</sub> )	7 kg	312.50
Al(NO <sub>3</sub> ) <sub>3</sub>	2.5 kg	236
Na <sub>2</sub> CO <sub>3</sub> - 0.1 M	1 L	26

This led to a total system cost of approximately \$164,000.

In addition, the team looked at a battery that could be used for the first thirty minutes while the fuel cell was warming up. Specifications can be seen in the table below.

Energy	70 kWh
Peak Power	100 kW
Power Density	4,000 W/Kg
Charge Retention	85% at 20,000 cycles
Operating Temperature	-50 – 75 °C
Price	\$12,000 - \$14,000

In the course of this project, several ethical issues were addressed. Team members did not always cite published work correctly, listen to each others' ideas or work as a team. Additionally, it was necessary to overcome issues of group members doing unequal amounts of work. Safety issues also needed to be considered, especially since the vehicle is capable of crashing and injuring those on the ground.

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## Resources

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I PRO 318 has been given great autonomy from the faculty advisor. The team leader and sub-team leaders are entrusted with the task of properly manage the time and assign tasks for each team member, which is an effective strategy for a large I PRO team.

The team consists of sophomore chemical engineering student who are getting one credit hour, senior chemical engineering students who are getting two credit hours, and other majors who are getting three credit hours. Works are assigned based on individual's knowledge levels as well as the expected workload associated with the varying level of credit hours awarded.

Sophomore chemical engineers are expected to contribute to the literature survey and provide the research summary to the sub-team leaders, who can then combine the results into written reports. Senior chemical engineering students take leading roles for the project design, while other majors provide expertise in their respective majors.

Since the goal of the I PRO is to attain tangible results, the quality of a student's work is judged instead of the amount of time one can self report, which is a system prone to abuse. The amount of time a student spends researching is of less importance than the final work submitted to the team.

The entire I PRO meets once a week at its assigned classroom, during which questions are brought up and answered across different subgroups and each subgroup reports its progress to the rest of the team. The team leaders then determine the next course of action and assign new tasks to subgroup team leaders who in turn divide those tasks among their members. The meeting generally lasts for the regular class period of 1 hour 15 minutes.

In addition, each sub-team is encouraged to meet at a convenient time and location for members in the team to get together and compile research results before the team meeting. The sub-team meetings generally occur once or twice a week and last for one hour.

Team members regularly exchange ideas and proofread each other's written reports through emails or igroup. No precise time tracking is needed for such tasks, since team members can work at their leisure and manage to get the work done before deadlines.

Money is spent for team building activities. There was one organized group outing to Giordano's Pizza, during which the team bonded and shared good food and nice conversation. Food was also bought for two of the team meetings toward the end of the semester as a reward for all the hard working done during the semester.

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