An Undergraduate Research Experience in New Technology Commercialization of PEM Fuel Cells

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In 1997, I was asked as a faculty member of Gonzaga University to participate on a project to develop a commercializable polymer exchange membrane fuel cell (PEMFC) technology for power plants in the 1-10kw range. The project was managed, sponsored, and funded jointly by Washington Water Power (WWP) and the Spokane Intercollegiate Research and Technology Institute (SIRTI). Our Gonzaga engineering team, which included students, was asked to perform manufacturability analysis and redesign of the fuel cell and to design a manufacturing system. The rest of the team consisted of a project manager from WWP, a commercial partner in Boston with the PEM fuel cell technology and experience, chemists from both Gonzaga and Eastern Washington University, and a small electrical contracting firm.

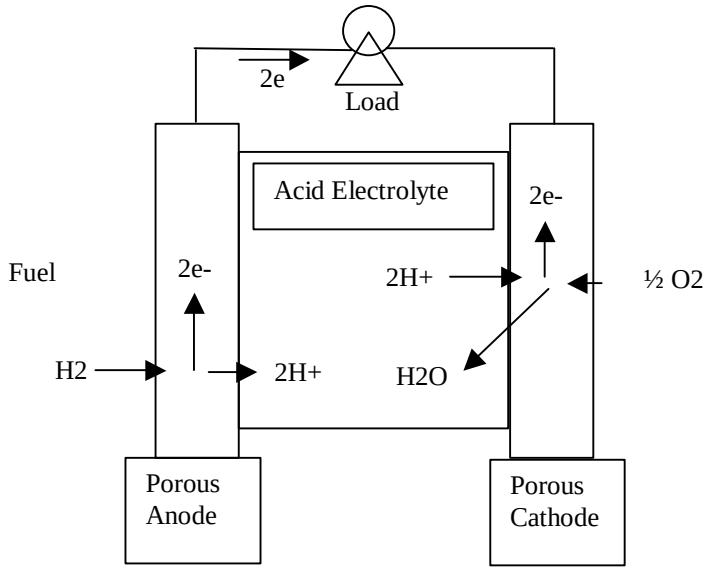
We interviewed and hired four mechanical engineering students to work on the project: three rising seniors and one rising junior. The rising seniors had already acquired much of the fundamental knowledge necessary through their coursework. The rising junior provided continuity if the project continued beyond the first year. In general, the students were the top students in their class and had the enthusiasm, initiative, and maturity to work on a real engineering project. Over the next nine months they learned about fuel cell technology and many technical aspects of engineering work. They also learned about working in a business environment on a marginally planned and undirected research and development project.

A fuel cell is a device that produces electrical energy from an electrochemical reaction between externally supplied fuels and oxidizers. Grove[1] first reported a successful fuel cell in 1839. Since then, researchers have investigated different types of electrodes, electrolytes, fuels and oxidants, and reaction kinetics affecting fuel cell performance. They have discovered that problems in thermo-fluids, material properties and geometry, electrical conductance and conversion, and manufacturing significantly influence fuel cell performance and economic viability. The technology benefited significantly from research for the space program and military applications since the 1960s. However, economic manufacturability and commercialization have not been overriding concerns in these publicly funded environments.

Despite the fact that we've been aware of the principles of fuel cell operation for more than 160 years, their widespread development and commercialization has been limited by materials, electrical power conversion technology, manufacturing techniques, and the relatively low cost of energy. This project was an attempt to develop the technologies to commercialize fuel cells.

Overview of Fuel Cells

A fuel cell, like a battery, is a device that produces electric current from an electrochemical reaction between the fuel and an oxidant, and consists of a cathode and anode separated by an ion-conducting electrolyte. An electric current flows between the cathode and the anode via an external conductor, while ions travel between them through the ion conductive electrolyte (Figure 1). Unlike a battery, in which the fuel and oxidant are actually a fixed part of the device and are consumed during operation, the fuel cell is supplied externally with fuel and oxidant. In this manner it behaves more like a motor generator set, which will continue to produce electricity as long as it is provided with fuel.



Anode: $2H_2 \rightarrow 4H^+ + 4e^-$

Cathode: $4e^- + O_2 + 4H^+ \rightarrow 2H_2O(l)$

Cell: $2H_2 + O_2 \rightarrow 2H_2O(l)$

Figure 1 Acid fuel cell electrochemical reaction

The figure above is of a general acidic-electrolyte fuel cell with hydrogen as the fuel and oxygen as the oxidizer. Hydrogen is oxidized at the anode, releasing electrons to move through the external circuit and perform electrical work. The resulting protons provide the balancing charge carriers, which are conducted though the electrolyte to the cathode where they combine with oxygen and with electrons from the anode side. The theoretical electrochemical potential of this cell is 1.23 volts, and it has a maximum intrinsic efficiency of about 83 percent.

One of the reasons fuel cells are so attractive is that they can achieve higher energy efficiencies than conventional combustion processes. The upper performance efficiency limits of combustion processes (35 – 40%) are the minimum efficiencies for practical fuel cell systems[2]. Free energy efficiencies as high as 60-80 percent have been obtained for fuel cells in laboratory settings. These efficiencies are higher than the 40-50 percent efficiencies achieved in fielded fuel cells, which indicates opportunities for improvement.

Losses in fuel cells reduce cell potential and release heat proportional to the difference between the real and reversible electrical work of the cell. Losses are primarily due to slow charge transfer across the electrode-electrolyte interface (activation polarization), mass transport limitations of ions near the electrode-electrolyte interface that produce concentration gradients

(concentration polarization), and ohmic losses in the electrolyte, electrodes, and the terminal connections. Losses are reduced by increasing operating temperatures, electrode active surface area (e.g., make electrodes highly porous), and electrode activity through better electrocatalysts; using highly conductive electrolytes and electrodes; and closely spacing current collection contacts to reduce current density. Figure 2 shows a typical cell potential vs. cell current (and efficiency) relationship and the influences of the losses. Additional ohmic losses occur from stacking cells to build up voltage, in connections, and in voltage and load control and conversion.

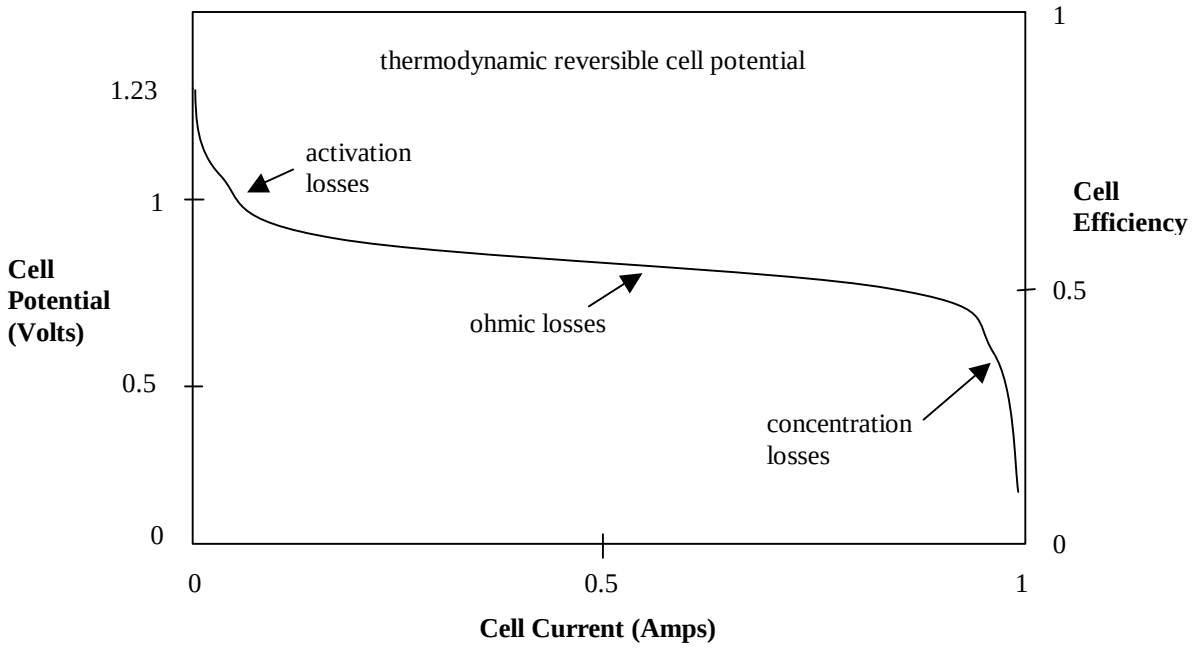


Figure 2 Cell potential vs. current[3]

Types of Fuel Cells

Fuel cells are classified based on the electrolyte they use. The most common types are phosphoric acid fuel cells (PAFC), molten carbonate fuel cells (MCFC), solid oxide fuel cells (SOFC), and solid polymer fuel cells (SPFC), which are now often designed around polymer exchange membranes (PEM) to make PEMFCs. Requirements of each of these electrolytes have led to a fuel cell type classification based on operating temperature as shown in the table below.

FUEL CELL TYPE	OPERATING TEMPERATURE
Polymer Exchange Membrane	<100ºC
Phosphoric Acid	180 - 210ºC
Molten Carbonate	600 - 700ºC
Solid Oxide	900 - 1000ºC

Table 1 Fuel Cell Types Operating Temperatures

Operating at higher temperatures speeds up reactions, reduces activation polarization, and increases diffusivity and convection to reduce concentration polarization losses. However, there are difficulties in designing for higher operating temperatures in corrosive environments (acidic

or alkaline). Thermal energy may be needed to initiate or maintain higher operating temperatures, though clever recovery and reuse of the electrochemical reaction heat and losses may mitigate the additional thermal energy requirements.

Despite the many potential benefits of fuel cells, there are still significant development and deployment needs such as cost reduction; innovation in fuels, materials, balance of plant (BOP), fuel flexibility and processing; solving system and system integration problems; and improving endurance and reliability. The reader can find lists of benefits and development issues on the National Fuel Cell Research Center web site at www.nfcrc.uci.edu. Because of the apparent simplicity and lower operating temperature, WWP and SIRTI chose to pursue PEM technology for their small plant fuel cell commercialization.

PEM Fuel Cells

Low temperature operation and insensitivity to CO2 contamination are important advantages of PEM fuel cells. Insensitivity to CO2 makes them attractive for use with hydrogen from reformed hydrocarbon fuels, especially if intermediate CO that would contaminate the PEMFC can be avoided. Significant work in PEMFC development is needed to reduce the costs of the polymer membrane and catalyzed electrodes, to scale up from laboratory sized units, to solve thermal and water management problems, and resolve balance of plant issues – all engineering problems.

The heart of the PEMFC is the membrane exchange assembly (MEA). The MEA consists of a thin (50-250 micron) ion-conductive solid polymer (such as Dupont Nafion) sandwiched between two catalyzed electrodes. The electrodes commonly consist of a supported catalyst (0.4mg/cm of 10 or 20% platinum on carbon) bonded with hydrophobic Teflon, and then bonded on to carbon paper or cloth. An electrode is pressed and bonded to each side of the membrane. Fuel and oxidizer must be distributed over the reactive surfaces of the electrodes, current must be conducted off the electrode's surfaces into the circuit, and the thin, flexible MEA must be physically supported. This is typically accomplished with a bipolar conductive separator plate with gas flow grooves formed into its surface. The grooves distribute a laminar flow of fuel and oxidizer over the catalyzed electrode, and the lands between the grooves collect current from the electrodes and to the external circuit. The MEA and the two separator plates form a single cell producing typically 100 –200mA/cm^2 of electrode surface at about 0.7V. Stacking the cells in a series circuit builds up the voltage to a desired level. The components and assembly of the PEMFC fuel cell and stack are shown in **Figure 3**.

The PEM electrochemical reaction with oxygen or air is the same as the one shown previously in **Figure 1**, in which the thin polymer film replaces the electrolyte. As the product of the cell is liquid water at the cathode, and protons crossing over from the anode are strongly hydrated, it is possible for water to "flood" the porous structure of the cathode electrode and prevent the oxidizer from reaching the reaction sites. The migration of hydrating water from the anode side can dry out the PEM and reduce performance by increasing ohmic losses at the anode-membrane interface. The heat, generated in the reaction and from electrical losses, can dry out the membrane. These are thermal and water management engineering challenges in PEMFC design.

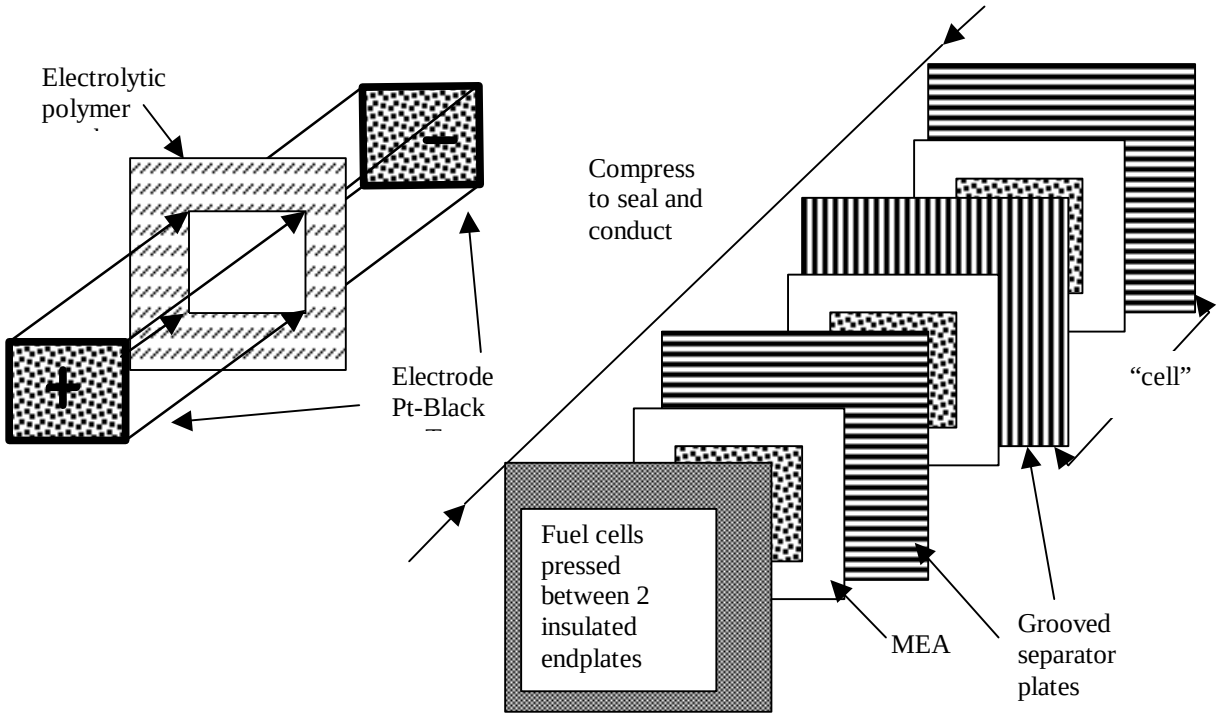


Figure 3 MEA and cell construction

PEMFCs are limited to low temperatures (< 100C) by the thermal stability of the PEM, but pressures to about eight atmospheres are used to achieve higher power densities. Both sides of the MEA must be maintained at similar pressures to minimize crossover migration of H2 through the membrane, which would reduce performance and increase the risk of an explosive H2-O2 mixture on the cathode side.

Despite progress in PEMFC technology, many significant engineering problems remain. The students had the opportunity to examine an emerging technology, and see the importance of resolving engineering issues in order to bring fuel cell theory to practical commercial use.

The SIRTI/WWP Project

The project provided engineering challenges for the students as well as the opportunity to learn about real-world project planning and management. Initially, the project goal was to commercialize and scale-up a laboratory-based PEMFC design and manufacturing process (from our fuel cell company partner) and to develop a 2kW plant to produce in volume. A lab, test stands, and office space had to be built for the project by the fall semester. The students began work on the project in early June.

The students started by learning about design processes and familiarizing themselves with PEM fuel cells. They studied requirement specifications, concept generation and evaluation techniques, functional decomposition, configuration design and evaluation, and parametric design and evaluation using John Dixon's Engineering Design and Design for Manufacturing textbook[4]. They performed web-searches and library research to learn about the state-of-art in PEM fuel cells and their manufacture. We developed a Mathcad[5] based model to study PEM fuel cell relationships between MEA reaction area, operating voltage and current, fuel and oxidizer flow and distribution, and the generated water and heat that would have to be removed. The students also generated conceptual designs for MEAs and fuel cells. They explored, documented,

and discussed concepts to physically support the thin electrodes and the membrane (5-10 mils thick) and to provide good electrical contact with the electrode surface to carry off charges to send to the external circuit. The concepts had to provide for reducing ohmic losses and electrode current density using many contacts on the electrode surface, while not restricting distribution fuel and oxidizer or dissipation of generated heat and water, over the electrode surface.

One student and I visited our commercial partner's site in Boston to learn and document their processes. We lost one day in Boston because of a contractual dispute between the partner and WWP/SIRTI, and were not allowed into the partner's facility. During the rest of the week, we learned about fuel cell operation and testing critical operation and design issues, stack design and assembly processes, and MEA fabrication processes. Upon our return to Spokane, the students prepared a report and presentation of our findings to the program team. Throughout the project, students were responsible for all the presentations to the program team and visitors, status reports at weekly program meetings, and design reviews. The key findings from our Boston trip are listed below.

- Water management is critical. Too much water can flood the MEA and block oxidizer from cathode reaction sites. Drying out a flooded MEA can take 8-12 hours. Too little moisture added on the anode side and/or too high an operating temperature will dry out the membrane. The dry membrane embrittles and fractures, allowing cross flow between the sides that reduce performance and can result in an explosive H2-O2 mixture.

- It can be difficult to select an operating point. Higher currents (to 1 A/cm^2) for more power will result in lower potential, higher ohmic losses, and excessive heat generation. Lower operating currents (0.1 –0.5 A/cm2) and higher voltages (0.7-0.8V) are preferred.

- The water and thermal management problems, as well as uniform distribution of fuel and oxidizer, increase with the size of the MEA. Our commercial partners had great success with 5x5 cm^2 MEAs. Our program plan was to develop 15x15 cm^2 MEAs.

- The formulation and application process of catalyst and binders to make electrodes is critical to the performance of the MEA. The laboratory-based electrode fabrication and MEA assembly process needed considerable modification to manufacture high volumes of consistent MEAs. The lab process required a considerable effort and process monitoring by trained laboratory specialists, compared to the planned manufacturing environment using less skilled personnel and more machine-performed functions.

- Our partner made bipolar separator plates by machining groove patterns into graphite slabs to distribute gasses. Graphite is preferred because of its conductivity and chemical inertness, but machining graphite is dirty, difficult, and expensive. It is not as attractive for large-scale production as it is for small volumes. We would have to find a way to reduce the costs of machining the plates (automation), or find some other manufacturing methods and/or material to make bipolar separator plates.

- Proper assembly of the stack is critical for sealing and electrical contact. A gasket between each pair of bipolar plates prevents pressurized hydrogen from escaping into the

atmosphere or crossing over to the O2 side. Cells (plate, MEA, plate) are built up in a frame between two metal endplates, and aligned with guide/tension rods through holes at the plates' perimeter. Tightening the nuts on the rod ends compresses the stack. Proper alignment, uniform tightening, and proper torque are critical for sealing and good electrical contact between the electrodes and the lands on the grooved bipolar plates.

In late August, we moved into new offices at SIRTI and had a change in program direction. The project manager decided to develop his own proprietary membrane polymer and new cell designs instead of working with our experienced Boston partner. An atmosphere of secrecy and competition developed between our partner and the Spokane group, and within teams in Spokane. Our new engineering task was to develop a see-through cell to test MEAs with new polymers, and to develop a cost model of a scaled up version of the commercial partner's process to meet the WWP's and SIRTI's original contractual obligations.

The students used the guided iteration design process to develop the test cell. The selected concept was a Plexiglas cell with pockets for separate current collectors to support the MEA. They chose this approach because it made it easy to test collectors of different materials and geometric configurations. After investigating several collector materials with low cost, acceptable conductivity, and good electrochemical stability, the students selected brass and stainless steel to form into a grate-spring configuration. The spring would provide pressure to make a good electrical contact between the collector and the MEA electrode. The students also wanted to optimize grate spacing to maximize contact area while maximizing exposed electrode area to the distributed gasses. They used estimates of resistivity from reference sources and rough measurements in mathematical models to select a reasonable spacing as a function of the electrode surface resistance, the collector material conductivity, and voltage-current operating points. The students designed the Plexiglas housing and gas distributing system, the sealing systems, the current collectors, and arranged for fabrication of the all subsystems. They then learned about contractor dependability (or lack thereof) while getting their designs fabricated. Conflicts and competing priorities between our jobs and jobs of other program teams in fabricator shops led to delays and to our having to find our own shops to build our parts.

The students finally assembled and tested their cell, but ran into a problem when they could not obtain a good reference MEA that was to have been supplied by another local team. They obtained a used MEA from our commercial partner in Boston, but it did not provide a reliable baseline to evaluate the test cell because its quality and condition were not known. At this time, the entire emphasis of the project shifted primarily to research, and we were asked to drop the test cell. The students were to help monitor testing for the chemists, which they did not find particularly interesting. They worked sporadically on the project through early winter, but most of them quit the WWP/SIRTI project and focused on finishing their courses.

The students had some novel educational experiences during the fall semester. We flew to Connecticut on the WWP corporate jet for a one-day business trip. We had a status meeting with our commercial partner the evening we arrived, and toured the International Fuel Cells PAFC manufacturing facilities and labs the next day before flying back to Spokane. The students were impressed by the professionalism and organization of the IFC operation compared to their experience with our program's organization, focus, and management. It had been a novel and

exciting opportunity for the students to see the types of work they might do as engineers in a technology business. The students were also involved in public relations activities such as opening receptions and visits from politicians and community leaders during this semester.

Senior Capstone Design Project[6]

The students choose to develop an MEA manufacturing system for their senior design project. They determined that the laboratory process they had documented at our commercial partner's operation could produce six MEAs per day. The cycle time included the technician's time and oven baking and heated press time, which were limited by the sizes of the ovens and presses. It also included careful handling of MEAs and electrodes to avoid exposure to CO in the air. We selected a production rate objective of 1000 2kW fuel cell stacks per year, which would require a production rate of 200 MEAs per day (eight hour shift). The project objectives and deliverables (statement of work) are shown below.

Objectives	Deliverables
• Design a new process to improve the old lab process • Identify key production parameters • Design a manufacturing line, capable of producing 200 MEAs per day, which shows significant cost and time savings over the old process. • Complete a line layout of suitable detail for a vendor to begin construction.	• Process Plan • Line design (equipment, layout, utilities, materials) • Schematic representation of line layout

Table 2 Summary of Statement of Work

The students decided to break the system down into three discontinuous process modules that produced batches of sequentially assembled components (Figure **4**): Toray Paper Pretreat, Electrode Fabrication, and MEA Assembly. Using three independent lines allowed the system to meet the constraints of the eight-hour shift and the long baking time, and facilitated quality checks of each component before it was assembled into the next higher component. It is costly to disassemble the stack and replace the MEA once it is produced and assembled into a stack, and it would needlessly expose the expensive membrane and platinum catalyst to damage and contamination.

The students simulated the processes and activity times with a discrete event modeling and simulation tool called SimProcess[7]. They experimented with capacities and times, working from the target 200 MEAs per shift throughput, to determine required process times and equipment capacities. They combined this information and process specifications to design and specify ovens, sprayers, presses, conveyors, racks, special tooling, and a 1500 ft^2 facility layout (Figure 5). Since some equipment was shared between two processes, routings had to be carefully designed to ensure that operations did not interfere. A sample equipment specification is shown in Table 4 below. The students also designed a sheet handling support, a cutter alignment jig, and an electrode/press alignment jig to support manufacturing. Detailed production instructions were prepared for each production module.

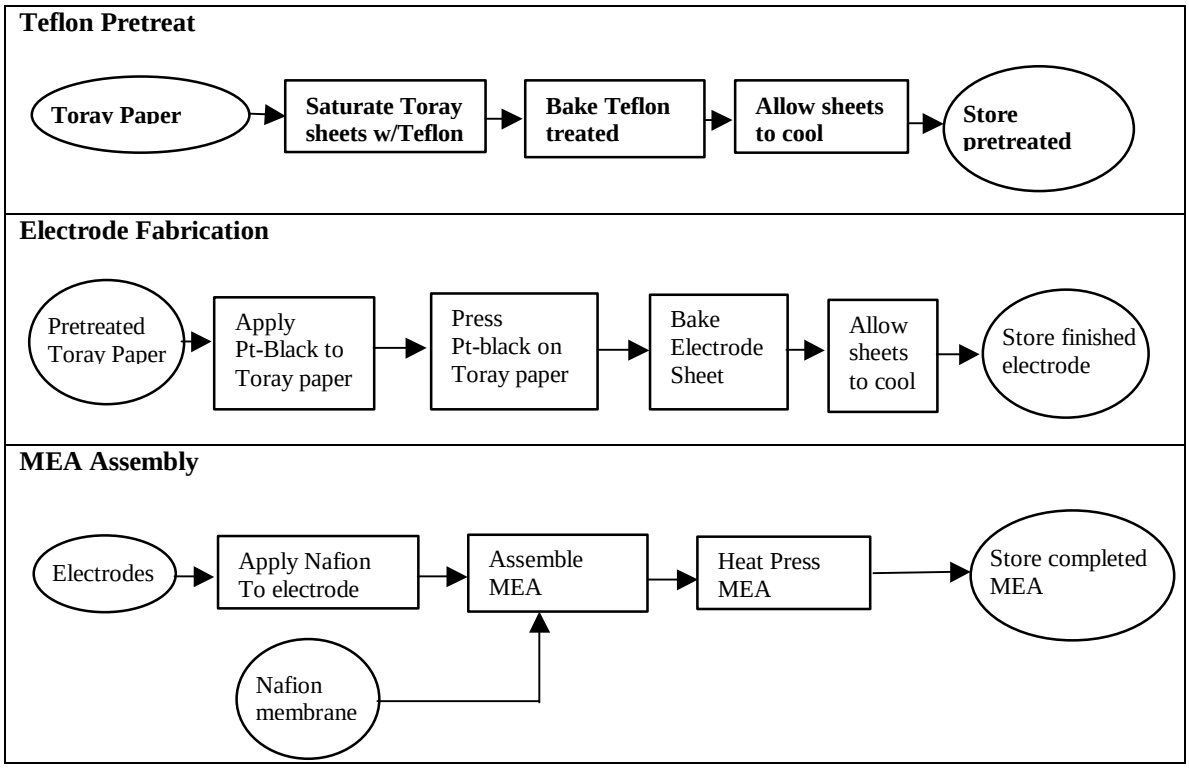


Figure 4 Breakdown of MEA Manufacturing Process

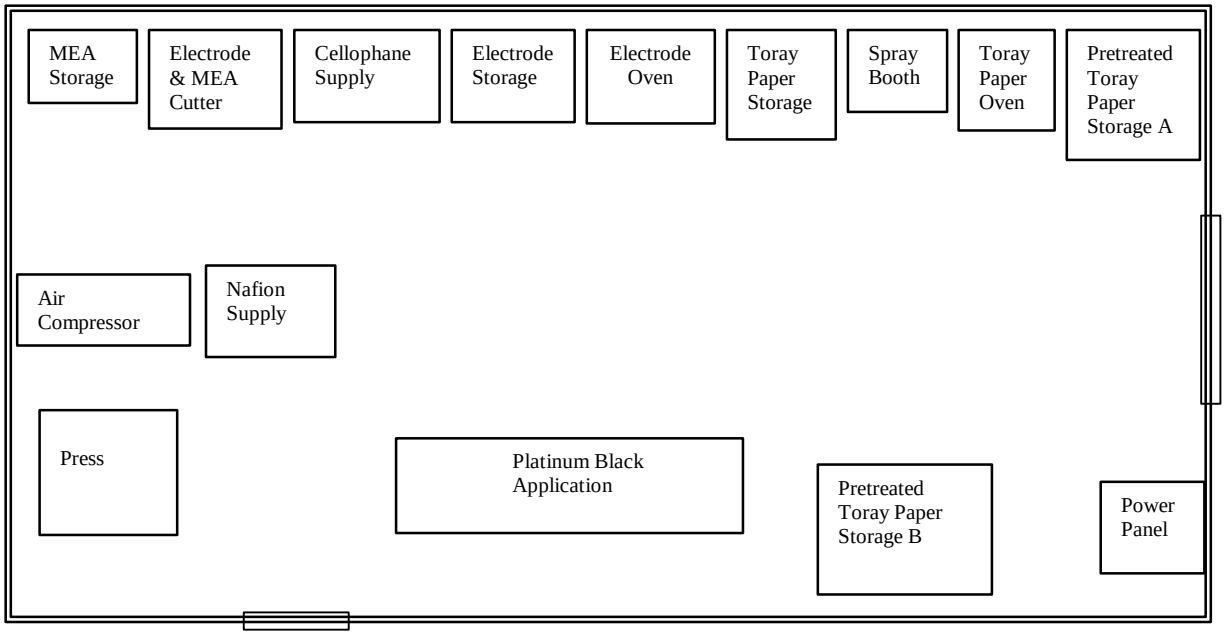


Figure 5 MEA Manufacturing Facility Layout

Equipment type:	Automatic spray conveyor
Process:	Platinum black application
Manufacturer:	Paasche
Machine:	F89-Sl-22(modified) & 4 A-BUF-4 spray heads
Price:	$35,000
Utilities:	1.5 kW, 24cfm(air) @ 35psi
Operators:	1/2

Table 3 Equipment Description

The students used SimProcess' activity based costing functions to find labor, material, and utility costs and used them in an economic analysis, along with a realistic estimated selling price and capital costs obtained from the equipment suppliers ($165,000). The results indicated $271,000 in after-tax annual profit for producing 50,000 MEAs per year. Including an estimated facility cost of $30/ft^2, the after tax ROI for this venture over five years would be over 30 percent.

Conclusions

The projects provided unique learning experiences for the students and for me. We learned how fuel cells operate and are designed, the key issues and difficulties in design, fabrication, and operation, and the difficulty of commercializing the technology. Inexpensive and readily available fuel cells still require development of improved materials and manufacturing processes, but it seems economically feasible to produce PEM fuel cell MEAs at reasonably high volumes.

The students learned how to conduct an engineering project, from requirement specifications through to manufacturing planning and design, and how to work with a variety of technical sources and tools. They worked with math modeling and simulation, with small and large fuel cell companies, and with fabrication shops. They witnessed conflicts between business partners, interpersonal and organizational politics, and the lack of management experience in planning and staying focused on entrepreneurial ventures. The students combined their theoretical engineering education; their newly acquired knowledge about fuel cell systems; and economic analysis, project planning, management, communication skills developed during their work experience to achieve their results.

The students grew professionally and technically with the experience. I believe they enjoyed their work, and felt a sense of accomplishment and pride in their results. One student, Vincent Yarnot, has written me about the experience.

"I loved every bit of the science, the design process, the testing, and the small leadership roles I got to take. Even though … the labs were poorly focused and often in turmoil, I always looked upon the situation as a learning experience. I feel that the experience helped me improve my group working skills. I also think that the design experience gave me a head start over many other fresh out of school engineers."

These types of real world experiences for students are invaluable, and perhaps necessary, to provide a complete undergraduate engineering education.

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