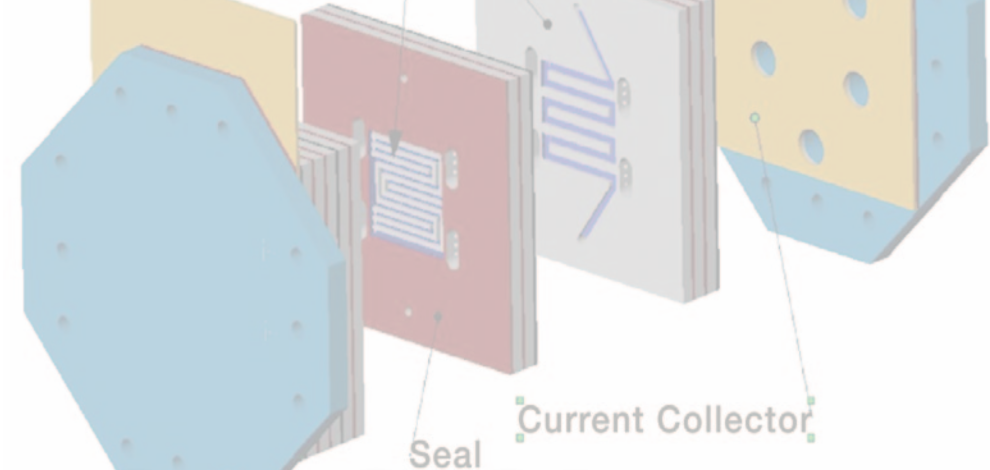

Bringing Fuel Cells to the Classroom

The University of Washington's Fuel Cell Curriculum

by Eric M. Stuve

In the high tech boom of the mid-1990s fuel cells began to attract widespread attention, expanding from a relatively small group of academics and industrial technologists to include an array of industrial firms, large and small, and venture capitalists. The popular media ran stories of fuel cells with quotes from automotive executives promising fuel cell powered cars by some not too distant year. Fuel cells would be more efficient and less polluting. They would revolutionize our driving habits, let us talk longer on our cell phones, and free us from the electric grid.

The only problem was that fuel cells are notoriously difficult to build, let alone at a cost competitive with other energy technologies. Apart from a few needed technological breakthroughs, fulfilling the promise of fuel cells depends every bit as much on the skills of a work force trained in the art of fuel cell engineering. Perhaps even more disturbing, there were few academics with any experience in building individual fuel cells and virtually none with experience in stacks or systems. This author belonged to neither group.

The Fuel Cell Design Project: An Exercise in Experimental Learning

In 1996 a group of faculty at the University of Washington sought to bring fuel cells into the classroom in the form of an interdisciplinary senior capstone design project. The group included faculty from the departments of Aeronautics and Astronautics (Reiner Decher), Chemical Engineering (myself), Electrical Engineering (Rich Christie), Materials Science and Engineering (Brian Flinn), and Mechanical Engineering (Per Reinhall). The project embarked on an ambitious goal: to design and build a fuel cell powered locomotive that would carry passengers and to have it ready for the College of Engineering's Open House in 1998. Table I summarizes the details of the fuel cell project.

Goals of the Fuel Cell Design Project

The technical goals consisted of design, fabrication, and operation of a hydrogen-fueled, 10 kW proton exchange membrane (PEM) fuel cell driving a one-third-scale locomotive pulling two passenger coaches. The educational value derived from students working in groups to bring about a successful demonstration of the fuel cell locomotive, in much the same way as a PhD degree is earned through completion of a successful research project. As the project was a capstone design project, students would also have to become familiar with writing proposals and cost estimation. The main educational objective was that, by participating in the project, students would learn the necessity of well-coordinated working groups, good communications within those groups, effective planning, along with the dedication, motivation, and resourcefulness needed for a project of this scope.

Structure of the Fuel Cell Project

Students were divided into four groups, one for the locomotive and the other three for basic components of a complete fuel cell: the single cell group, stack group, and systems group. The

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Table I. University of Washington Fuel Cell Design Project.

Technical goals	Fuel cell locomotive 10 kW hydrogen-fueled PEM fuel cell 1/3-scale locomotive with 2 passenger cars
Educational goals	Experiential learning, interdisciplinary experience, teamwork, communication skills, planning and proposals, design, costing, fabrication
Participating disciplines ***Primary participants**	Aeronautics and astronautics, chemical engineering* (more than 50 students), electrical engineering, materials science and engineering, mechanical engineering* (more than 100 students)
Group organization	Single cell, stack, systems, locomotive
Report requirements	Proposal (week 2), progress reports (1-2 throughout quarter), final report (week 10), oral presentations accompany written reports
Grading	Individual grade: lab books, peer effort evaluation, instructor observation; Group grade: report quality and content, group planning and project execution, attention to safety
Technical accomplishments	Single cell group: MEA preparation procedures, small (5 cm^2) area single cells; best performance 0.26 mA/cm^2 at 0.6 V; Stack group: large area (100 cm^2) 7–cell stack, variety of flow field plate configurations and materials; Systems group: test stations for small and large area cells, temperature and humidity measurement and control; Locomotive group: 1/3-scale locomotive, passenger coaches

single cell group was charged with developing procedures for making membrane electrode assemblies (MEAs) and a single cell (about 5 cm^2 active area) to test them. The stack group was charged with building a functional stack with larger scale (about 100 cm^2 active area) cells and making flow field plates, gaskets, and related hardware. The systems group was charged with design and construction of test stations with fuel and air flow and conditioning, heat exchange system, and sensors for monitoring and controlling fuel cell operation. The locomotive group was responsible for the locomotive and passenger cars.

In each quarter students prepared a proposal, one or two mid-term progress reports, and a final report. All reports had written and oral requirements. The proposal, due in the second week, was to focus the group's work for the remainder of the quarter. It forced the group to get together quickly and plan their time. The progress reports gave the groups an opportunity to review their work to date and seek help from faculty and other students. The final report was the main event for each quarter. Each group worked hard to accomplish what it planned eight weeks before, reported its successes, and accounted for what did not work or could not be done.

Because of the group nature of the course, and its focus on technology with uncertain outcomes, grading was challenging. Student grades consisted of individual and group components. The individual grade was based on instructor observations of student performance and participation, student and peer evaluations, and the student's lab book. The group grade was based on the quality and content of the report and evaluations by group members.

Lessons Learned and Course Outcomes

The pace of progress proved frustratingly slow. Some of the recurring problems included (*i*) significant dimensional changes of large area Nafion® membranes during catalyst deposition, (*ii*) designing effective seals for stacks, (*iii*) poor contact resistance in single cells and stacks and students' ability to apply Ohm's law, and (*iv*) the near futility of attempting to control humidity level in feed gases. Well-written final reports were crucial in passing along the lessons learned.

The students succeeded in many aspects of the project, although the overall goal of a fuel cell powered locomotive proved elusive. In the first year a MEA was successfully tested in a single cell attached to a test station, all fabricated by the students themselves. The system produced very small amounts of power, on the order of several mW/cm^2. Each year a new group of students worked on the project and moved it further along. Single cell performance slowly increased and eventually reached a level of 0.26 mA/cm^2 at 0.6 V. Several MEA procedures were developed, in which catalyst was applied to the membrane by direct deposition, airbrush, or ink jet printer. Several versions of test stands were built including systems for small single cells and large area stacks. A fully functional, large area, multicell stack, shown in Fig. 1, was tested in 2001. A small area stack developed by the single cell and stack groups is shown in Fig. 2.

Despite the lack of a fuel cell, a locomotive and two passenger cars were built. The stainless steel locomotive had a small cab big enough for a person

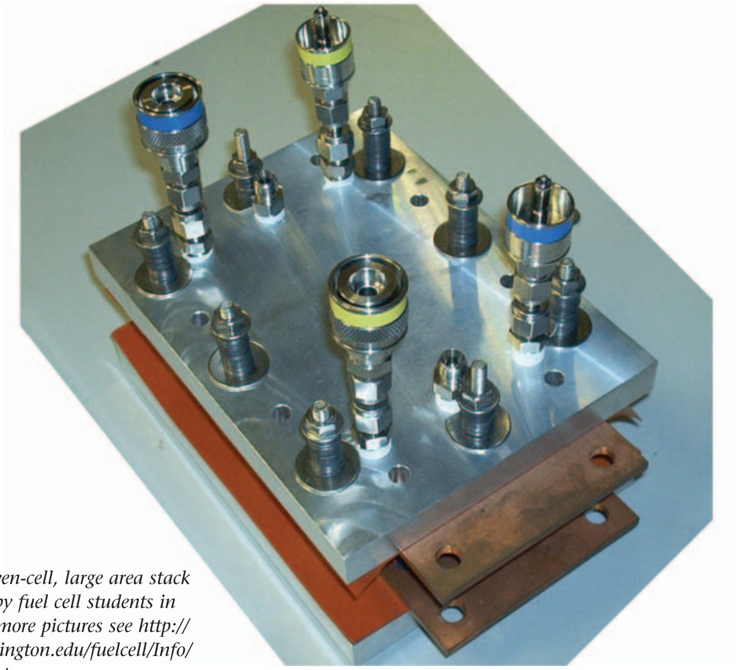

Fig. 1. *Seven-cell, large area stack developed by fuel cell students in 2001. For more pictures see http://depts.washington.edu/fuelcell/Info/FAQ/FAQ.htm.*

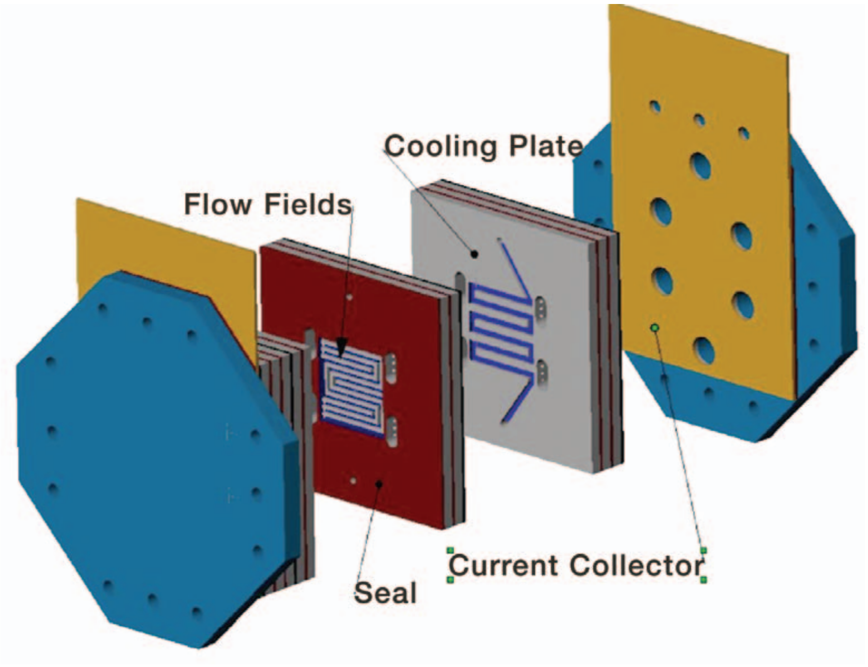

Fig. 2. *Small area stack developed by the single cell and stack groups in 2003.*

to stand in; it looked like a telephone booth on wheels! The passenger cars had hand crafted mahogany benches under a canvas canopy. They seated four people in a festive style. We never did lay track, which would have turned out to be the biggest problem. Standard rail is heavy, 110 lb per yard, and expensive. Once it is in place one does not move it, so this is not the right project for a weekend Open House event!

Safety

The most important aspect of the project was safety, and the most significant safety problems developed in the end-of-quarter rush. Project work always takes longer than expected and students trying to achieve the goals they established in their proposal will work around the clock to get the last result. With chemical systems this is a formula for disaster. To discourage such behavior instructors stressed that students were not graded on accomplishment alone; safe operation was most important. The reports, lab books, and evaluations provided ample material for grading. The best groups were those that planned ahead, achieved some modest (and sometimes spectacular) accomplishments, and reported both accomplishments and mistakes at the end of the quarter. One group even remarked that it seemed that those who made the most mistakes got the highest grades. In effect, they were right.

There was one hydrogen explosion in the first year of the project. The explosion occurred as the single cell group was shutting down a run of their fuel cell. The test configuration had excess hydrogen from the fuel cell exhausting through a water trap and into a Bunsen burner where it was burned. The water trap, a 1 L Erlenmeyer flask partially filled with water, was to prevent accidental backflow of air into the hydrogen line. Upon shutting off the hydrogen flow the Erlenmeyer flask exploded, making a sound that was heard throughout the four-story chemical engineering building. The three students, their ears ringing for a half-hour afterward, suffered minor cuts from the exploded flask, which had been turned into glass dust. One student, who did not have full eye protection, escaped serious eye injury only by the limited protection afforded by his eyeglasses. Experimental work was halted for nearly a year until the incident was thoroughly investigated, which became part of the project. The investigation revealed that the Bunsen burner was not suited for use with hydrogen, as explained further below.

A Fuel Cell Curriculum Emerges

Fuel Cell Engineering

With the fuel cell project underway the need for formal coursework in fuel cell engineering became readily apparent. Tables II and III list details of the fuel cell curriculum in its present configuration. In 1998 we offered the first course in Fuel Cell Engineering (ChemE 445) to a group of University of Washington (UW) students and by distance learning to students worldwide. Since that time 250 students have taken the course, including more than 80 by distance learning. Distance learning students have come from companies like Ballard Power Systems, UTC Fuel Cells, Boeing, HP, and Ford, and other universities throughout the world.

As there was no suitable textbook, a complete set of course notes had to be developed. Monographs available at the time emphasized the electrochemistry of fuel cells, but our experience with the

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Table II. University of Washington chemical engineering fuel cell curriculum.

ChemE Course No.	345	445	446
Title	Introduction to Fuel Cells	Fuel Cell Engineering I	Fuel Cell Engineering II
Credits (quarter)	3	3	3
Prerequisites			
Fresh. Chem.			X
Fresh. Phys.	X		X
Intro. Thermo.	X		
Fluid Mech.	Recom.	X	
Heat Transfer			X
Students			
Juniors	X	X	X
Seniors	X	X	X
Graduate students		X	X
Requirements			
Homework	X	X	X
Design Project	X	X	
Exams	X	X	X
Texts			
Instructor Notes	Req.	Req.	Req.
FC Handbook[7]	Recom.	Recom.	
FC Sys. Explained[8]	Req.	Recom.	
Perry's Handbook[3]		Recom.	
Developer	Arvindan	Stuve	Adler
First offered	2002	1998	2003

Table III. Topics Covered in UW fuel cell curriculum.

ChemE Course No.	345	445	446
Title	Introduction to Fuel Cells	Fuel Cell Engineering I	Fuel Cell Engineering II
Introduction	Energy	Chemolectricity	
FC Thermodynamics	Reversible Irreversible Nernst Eq. Overpotentials Efficiencies	As in 345, but more detail	Review
Fuels	Overview	FC Reactions Fuel Processing	
Fuel cell operations	Overview	Polarization Curves	Diagnostics Voltammetry Impedance Current Interrupt
FC Technologies	Survey PEM, AFC, PAFC, MCFC, SOFC	PEM, SOFC	PEM, SOFC
Single cells	Overview	Overview	Electrolytes Ion Transport Cross-over Mixed Conduction Electrocatalysis Degradation Three Phase Boundaries Mass Transfer Water Management
Stacks	Overview	Electrode Models Pressure drop Flow field Plates Interconnects	Interconnects
Systems	Overview	Flow diagrams Power cycles SOFC-GT system PEM system Systems integration	
Power conditioning	Power Devices DC-DC Converters AC-DC Converters		
Applications	Automotive Stationary Portable Power		
Safety	Codes	Hydrogen safety Oxygen safety Codes	

project showed that engineering was the more immediate need. Again, the fuel cell project dictated the organization and extent of material to be covered. The course was organized around polymer electrolyte membrane (PEM) fuel cells by four major topics: single cells, stacks, systems, and safety. Each topic was developed to give students sufficient background for developing their respective components in the project.

The Springer model[1] introduces the mass balance of a PEM fuel cell and the water management problem. Despite the simplicity of this model, it remains a key element of fuel cell pedagogy, not unlike the Bohr model of the hydrogen atom is for quantum mechanics. The more detailed model of Bernardi and Verbrugge[2] introduces the effect of pressure differential and the concepts of self-hydration and anode water removal.

Stack engineering is developed through flow field plate design, pressure drop, and heat transfer. Simplifications and correlations are used whenever possible. For example, pressure drops in serpentine flow fields are estimated by laminar or turbulent flow equations adapted for flow in rectangular channels.[3] The effects of bends in serpentine flow fields are neglected, as are changes in flow rate and gas composition due to reaction along the channel. While these significant simplifications no doubt affect the accuracy of the final answer, they allow for easy analysis of changes in fuel cell performance as a function of the design and operating variables. Literature models, such as those of Fuller and Newman[4] and Yi and Nguyen[5] give students a feel for more detailed analysis of fuel cells.

The overall fuel cell system is especially amenable to traditional chemical engineering mass and energy balances. The systems section covers humidity control, temperature control, fuel recycle, and their parasitic load on the system. Students realize the need for a systems level approach as optimizing fuel cell performance may come at the expense of higher parasitic load.

Safety aspects are covered at the end of the course. Students are introduced to the unusual aspects of hydrogen and hydrogen flames. Hydrogen has an especially wide range of explosive compositions in air, as is well known by most fuel cell researchers. Less well known are the unusually fast flame velocity and significantly smaller flame diameter relative to other combustible gases, such as methane. The minimum flame diameter is the smallest hole that a flame can pass through at atmospheric pressure without quenching. This diameter, approximately 0.6 mm for hydrogen, sets the minimum safe leak diameter. A leak through an opening larger than the minimum flame diameter has the potential to ignite and produce a flame that could, by virtue of its high flame velocity (about 300 cm/s), travel back into the fuel cell and potentially cause an explosion. This lesson was learned first hand in the fuel cell project.

The extreme reactivity of pure oxygen is illustrated by analysis of the launch pad fire in the Apollo 1 command capsule that took the lives of three astronauts.[6] Static electricity hazards caused by gases and non-conducting liquids flowing through insulating tubes are illustrated by analysis of the TWA 800 fuel tank explosion that occurred in July 1997. In the fuel cell design project the systems group experienced several instances of static discharge that, fortunately, occurred without incident. A review of relevant safety codes completes the safety section.

Reaching a Wider Audience: Introduction to Fuel Cells

With the popularity of the fuel cell project growing, additional courses were added beginning in 2002. A survey course, Introduction to Fuel Cells (ChemE 345) was developed by Nallakkan Arvindan, a graduate student in my research group at the time. Arvind, as he likes to be called, received a prestigious Huckaby Fellowship from the University of Washington for his proposal to develop the course and teach it by the method of Virtual Tutored Video Instruction (VTVI). This involved having on-site tutors for distance learning students. The VTVI method works well when several people at a given site take the course together. Arvind followed the Fuel Cell Handbook[7] in developing his course. The course covers the five technologies of fuel cells (PEM, alkaline, phosphoric acid, molten carbonate, and solid oxide) along with a discussion of power conversion and applications.

Comparative Studies of Fuel Cell Technologies: PEM and SOFC

In 2003 Stu Adler developed a follow-on course, Solid Oxide Fuel Cells (ChemE 446) for the fuel cell engineering series. This course focused on solid oxide electrolytes, electrodes, and systems, with special emphasis on combined heat and power systems such as a solid oxide fuel cell/gas turbine combined cycle (SOFCGT).

Instead of focusing on a single fuel cell technology, Adler recognized that students would achieve a deeper understanding of fuel cells through comparative study of two technologies. Thus, the two fuel cell engineering courses (ChemE 445 and 446) were restructured in 2005 to cover both PEM and SOFC technologies in both courses. The 445 course focused on engineering aspects of stacks and systems, while the 446 course focused on molecular level details associated with electrolytes, electrocatalysis, and transport phenomena.

A special moment midway through the first term of the newly reorganized 445 course proved the merit of the comparative approach. In a lecture on the energy balance of an SOFC system, Adler noted that SOFCs typically operate with a large excess of air, needed to remove waste heat from the fuel cell. Puzzled, I remarked, "That means the SOFC operates adiabatically." "Of course, how else can it operate?" Adler responded. "When it operates isothermally, like a PEM," I said.

That was the "Aha!" moment. A high temperature fuel cell like a SOFC cannot use a liquid coolant, thus requiring excess air as thermal ballast, which in turn, is recovered in the gas turbine. By contrast, a large excess of air induces a large parasitic load in a PEM fuel cell, so liquid cooling and near isothermal operation is generally preferred. Such moments were repeated several more times throughout the quarter. The students enjoyed seeing their instructors puzzle over competing descriptions of fuel cell phenomena.

Fuel Cells in the Unit Operations Laboratory

To give every chemical engineering student the opportunity to study fuel cells we implemented a fuel cell system for the unit operations laboratory. The original installation was a test station and fuel cell from the fuel cell design project, but that proved too specialized for a teaching laboratory. A commercially available instrument, the UO-1000 from TVN Systems, proved ideally suited for the laboratory and was installed in 2004. This system incorporates a three-cell PEM stack, test station with temperature and humidity control, electronic load, and computer control and monitoring system.

ECS Short Courses in Fuel Cells

The Fuel Cell Engineering course has been offered as an ECS short course since 2002. At the Los Angeles ECS Meeting in 2005 a new version of the course was taught in collaboration with Hubert Gasteiger. The course consisted of two sessions: the morning session on electrochemical fundamentals (Stuve) and the afternoon session on current issues in PEM fuel cells (Gasteiger). The 2005 course was well attended and received good reviews. It will be offered again at the Cancun ECS Meeting in October 2006. In addition, a SOFC short course (Stu Adler and Anil Virkar) was added in 2005, and will be offered again at the next ECS meeting hosting a major SOFC symposium.

Concluding Remarks

The fuel cell project and related curriculum is an excellent example of integrating research and education. A new curriculum was needed to move the design project further, while project experience determined the new pedagogy. Bringing fuel cells from the laboratory to the classroom has been a challenging experience, made even more rewarding by the opportunity to work with so many energetic and committed students.

I have been fortunate to work with many great colleagues at the University of Washington and wish to acknowledge them here. Bruce Finlayson encouraged me to pursue my interest in fuel cell education. Barbara Krieger-Brockett and Bill McKean took over my teaching duties in 1998 so that I could develop the first fuel cell engineering course. Michael Campion generously placed the distance learning resources of EDGE at our disposal. Other faculty members involved in fuel cells include in Chemical Engineering, Stu Adler and Dan Schwartz; in Materials Science

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and Engineering, Raj Bordia; and in Mechanical Engineering, Joyce Cooper, Phil Malte, and John Kramlich. The Mechanical Engineering department has developed an energy curriculum that includes heavy emphasis on fuel cells. More information on that program can be found at http://faculty.washington.edu/malte/course.html. The fuel cell design project continues in the Mechanical Engineering department under the direction of Reinhall and Cooper.

The fuel cell design project was supported with funds from the NSF-ECSEL program, the University of Washington College of Engineering, and Chevron. The unit operations fuel cell laboratory was supported by the Camille and Henry Dreyfus Foundation and UTC Fuel Cells. On behalf of my colleagues I extend our sincere appreciation for this support.

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