A Theme-Based Course: Hydrogen as the Fuel of the Future

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There have been numerous reports of capturing student interest in basic chemistry topics by connecting the topics to applications. A search of this *Journal* for the topic "applications" netted 335 references including topics such as fuels and $CO_2(1)$, clathrates (2), swimming pool chemistry (3), chemistry of cement (4), grease (5), and biodiesel (6). Here we report the result of basing an entire course around a single application: the question of "Is hydrogen the fuel of the future?" It was found that focusing on this relevant topic enhanced student performance in the course by nearly a full grade level (Figure 1). Since a search on "hydrogen fuel" in this *Journal* netted only one hit more recent than 1988 (7), (and that is a discussion of ethanol) several resources are included in the online material including laboratory exercises in support of the hydrogen question (Supplement A and topics listed in Table 1). At the end of the course, students are required to write a paper supporting their position on the hydrogen question. The paper must include data they collected in the laboratory. Examples of student papers are available in the online material.

Context

The course that used this theme is a one-semester introductory chemistry course designed for engineers and uses a text written specifically for this audience (8). A majority of the students are engineering majors with strong math and physics skills. The single-semester format precludes in-depth treatment of organic structures, and solution-based descriptive chemistry is curtailed. This course has been offered at this university for nearly a decade and student performance has been fairly consistent over this time. Statistics for the six years prior to the theme-based semester are shown in Figure 1. A diagnostic quiz designed to identify topics that the students are weak in is given within the first two days of the semester. (A copy is available in the online material.) This first quiz yields an important benefit; it detects any bias for prior student knowledge among students in a given semester. The data reported in Figure 1 show that the 2008 class—the theme-based semester-was within one standard deviation of all previous classes. It should be noted that class performance on the diagnostic quiz has been consistent over the eight years the exam has been given, hence, the small deviation. Further, the course has consistently emphasized applications; a single-theme format was chosen with no particular expectation that student performance would improve.

Evidence that the theme-based organization enhanced student performance is shown in Figure 1. Four quizzes are given during the semester in addition to the diagnostic quiz. The scheduling of quizzes and content of the questions has been consistent over the seven years indicated. The data in Figure 1 reveal two differences between the theme-based course in 2008 and previous renditions: First, in 2008 student performance on exams was significantly better than previously. It should be noted that although instructors can bias such results since they are in control of exam questions and so forth, this course has always been taught by the same instructor and there was no preconcep-



Figure 1. Data on student performance: average grades for students in 2008 (50 students) and 2007 (30 students) compared with average grades for over 300 students from 2002 through 2007.

Table 1. Laboratory	Exercises, Topics,	, and Referenc	es in Support of
the Questi	on: Is Hydrogen th	ne Fuel of the l	Future?

Exercise	Topics included	Reference
H ₂ Generation		
From Water	Gas laws; Reaction stoichiometry; Acid solution; Charge on an electron; Avogadro's number; Definitions: amp, watt	9
With Active Metal	Gas laws; Reaction stoichiometry; Ionization energy; Electronegativity	10
Generation of Electricity	,	
Solar cells (TiO ₂)	Molecular orbitals; Band gap; Conductivity in oxides; Molecular shape	11
Solar cells (Cu ₂ O)	Molecular orbitals; Oxide band gap; Oxide conductivity	12
H ₂ Storage		
A paper exercise	Thermodynamics	
H ₂ Usage		
Hydrogen fuel cell	Bands in semiconductors; Molecular shape; Gibbs energy; Oxidation numbers; Electrochemical potential; Nernst equation	13
Methanol fuel cell	Gibbs energy; Oxidation numbers; Electrochemical potential; Nernst equation	14

Active Metal —	Metal Cost			Molar Mass	Electrons	Electron Cost/	Cost ^a /	Fuel Cost ^b /
	\$/lb	\$/kg	\$/mol	(g/mol)	per Metal	(\$/mol)	(\$/tank)	(\$/mi)
Mg	3.00	6.61	0.161	24.3	2	0.0804	305	1.91
Al	1.52	3.35	0.0904	27.0	3	0.0302	115	0.72
Zn	0.40	0.88	0.0576	65.4	2	0.0288	110	0.68
Battery ^c							58,800	368
Household elec	:tricity ^d						104	0.65
Gasoline ^e							32	0.20

Table 2. Cost of Generating Hydrogen from the Active Metals Compared with Electrochemical Generation and Gasoline

^aTank cost based on 3.8 kg of hydrogen or a range of 160 mi. ^bA hydrogen-powered car with a 3.8 kg tank of hydrogen that runs160 miles. ^cThe batteries cost \$30. ^dThe household electricity costs \$0.17 per kW h. ^eGasoline costs \$4.00 per gallon and the car has an 8-gallon tank and gets 20 miles per gallon.

tion that the theme-base approach would enhance performance over the previous applications-based approach. Indeed, it was only at the point of assigning final grades that the instructor was struck with the significantly enhanced performance. The second difference from previous editions of the course is that student performance was more consistent—the class average on the first two quizzes was identical and the third very close to the same. For comparison, data from the 2007 version of the course are shown. Typically students find themselves in a crunch during part of the term and neglect their chemistry class; quiz grades slump at this time. The 2008 class was unique with no slump. This enhanced and consistent performance is attributed to getting and holding student attention by relating each section of the course to the hydrogen theme.

Laboratory Exercises and Course Topics

Hydrogen energy issues relate to every section of the course. Early in the semester, Avogadro's number is related to atomic mass, the gas laws, and the role of electrons in chemical transformations. In the first laboratory exercise, Avogadro's number is determined from the electrolysis of water (9). Students report that calculating Avogadro's number from their data makes the concept of a mole more tangible. Reaction stoichiometry and exchange of electrons in a reaction are reinforced by determining the atomic mass of an active metal using the hydrogen equivalent of a metal (10). These two exercises are brought into the hydrogen fuel issue by having the students calculate, based on their data, the cost of operating a hydrogen fuel car using hydrogen generated from electrolysis or active metals (Table 2). To compare the cost of operating a car with hydrogen fuel versus gasoline, data from a hydrogen-powered car that reports going 160 miles on 3.8 kg of hydrogen are used. Thus the "tank cost" listed is the cost of generating the 3.8 kg of hydrogen—no other associated costs are included.

Electrolysis using a battery (\$368 per mile) is spectacularly expensive. Even at \$4.00 per gal and 20 mi/gal, gasoline comes to \$0.20 per mile—hydrogen clearly has a way to go if electrolysis is used. At this juncture, advanced students may realize that using a battery and using an active metal (Zn) are electrochemically reasonably equivalent. If this issue is not brought up at the beginning of the course, it can be pointed out near the end of the course when electrochemical processes are discussed.

The cost of generating hydrogen using electrolysis with batteries or household electricity is not currently competitive, so the course examines alternate methods for capturing energy and storing it as H_2 . A method that is accessible to students is solar cells. The laboratory examined two such cells: the Grätzel cell based on a dye-sensitized TiO₂ and a simpler Cu₂O cell. Both of these cells can be understood from a molecular orbital view of band gaps. In this regard, the Cu₂O cell is particularly instructive since CuO is an insulator, Cu₂O a semiconductor, and Cu a metallic conductor. The electrolyte in the Cu₂O cell is a salt solution and students can easily construct the cell. The Grätzel cell is a bit more complex because the dye acts as an antenna to collect visible photons to effect charge-carrier generation. More advanced courses can discuss the HOMO-LUMO gap in the dye and matching energy levels between the collector dye and the acceptor semiconductor. Both cells illustrate the need to chemically "complete the circuit" to make a solar cell. At the present time, these solar cells are not sufficiently efficient to compete with silicon solar cells.

Utilization of hydrogen to produce water is the reverse of the generation of hydrogen and oxygen from water. Realization of this relationship leads students to quickly realize that it is likely that the entire process requires a net input of energy since no process is 100% efficient. Efficiency is a nice transition into a general discussion of thermodynamics and entropy and a specific discussion of the second law. This is a good point in the semester to introduce advertisements for running cars on clean and efficient water that produce just water. It is a sad commentary on the general level of scientific understanding that such advertisements are produced and broadcast.

Claims of vehicles running on water are particularly trivial to find on the Web. This leads to a discussion of the distinction between vetted scientific claims and claims or sources found on the Web. Writing a paper discussing prospects and barriers for hydrogen to serve as the fuel of the future is one of the course requirements. So these claims on the Web also serve the purpose of reinforcing the message that a Web source is not an acceptable source unless the claims are vetted via a peer review or similar process.

In the laboratory, students use a combination of a silicon solar cell and a fuel cell to power a model car. A tungsten–halogen lamp is used as a solar simulator to illuminate the solar cell. It is found that the solar cell coupled to the fuel cell generates hydro-

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Table 3. Gravimetric and Volumetric Energy Density	
of Various Energy Carrier Alternatives	

Carrier	Energy [Density	CO ₂ Produced		
	(kJ/mL)	(kJ/g)	g/(mL fuel)	g/(g fuel)	
H ₂ at 1 atm	0.0128	143	0	0	
H ₂ at 1407 atm	18.0	143	0	0	
Methanol	18.0	22.7	4.35	1.38	
Octane	36.5	52.3	38.8	3.08	

NOTE: Details of the calculations can be found in the student papers in the online material.

gen more rapidly than a battery connected to an electrode in an acid solution. The fuel produced is stored over water and used to power the car. Unfortunately, the hydrogen fuel cell membrane assembly is fragile, so this is a bit of a black-box exercise: the students can use the fuel cell, but they do not get a good sense for how it works. Thus, the hydrogen fuel cell exercise is followed by a methanol fuel cell exercise. The methanol fuel cell membrane assembly is less fragile so the students can assemble a fuel cell using methanol, a stainless steel screen, a membrane electrode assembly, and two large band aids (14). Seeing the inside of the cell helps students visualize the circuit that is the fuel cell. Of course, the methanol fuel cell produces CO₂ (or CO) in addition to water, which returns to the subject of CO_2 generation as a by product of energy usage. The issue of storage volume leads into the issues of gravimetric and volumetric energy density and the value of various fuel choices (Table 3). The conclusion is that gasoline and other condensed-phase substances are hard to beat.

The advantages of a condensed-phase fuel leads to the current, cutting edge research questions: Can hydrogen be stored in a condensed phase in such a way that it can easily be stored and released? If a hydrocarbon is the storage medium of choice, can CO_2 be efficiently and economically captured and sequestered? The ultimate answers to these questions will clearly affect the lives and futures of all of our students.

A recent article (15) makes the point that it is actually the strong oxygen–carbon and oxygen–hydrogen bonds in water and carbon dioxide that are responsible for energy release upon combustion. This is an interesting thermodynamic discussion to add to this unit.

In summary, this experience has demonstrated that keeping a course grounded in a consistent and relevant application can be an effective method for improving student engagement and performance.

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Supporting JCE Online Material

http://www.jce.divched.org/Journal/Issues/2009/Sep/abs1051.html

Abstract and keywords

Full text (PDF)

Links to cited URLs and JCE articles

Supplement

Laboratory exercises in support of the hydrogen question

Example student papers Diagnostic quiz