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In the Classroom

The Elements of a Chemistry Case: Teaching Chemistry Using the Case Discussion Method

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…Case Discussion Method pedagogy could strongly impact introductory chemistry classes…

We have recently introduced the Case Discussion Method as a viable pedagogy for the teaching of chemical principles in a real-world context to introductory level students. This article describes the Case Discussion Method and discusses the critical components in case teaching. Hommers Mining Dilemma was written to teach various principles of electrochemistry in the context of copper mining in a first-year chemistry class; this case is included as an example. The case-teaching note summarizes the case, illustrates its use in class, and provides analysis of the scientific issues.

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Introduction

The reform of chemistry curricula is both promising and challenging as past teaching methods are examined in light of more current educational goals. In the past, many chemical educators chose a traditional lecturing style as it allowed for maximum content coverage and it was the mode with which they were most familiar. In recent years, the effectiveness of the traditional unbroken lecture method has come under the scrutiny of science educators for its inability to reach students with a wide range of abilities and learning styles, and the passive atmosphere it creates in a classroom. When an instructor chooses to use an alternative pedagogy, there is often concern about whether portions of the course content are sacrificed [1]. This is a common concern, though it is our impression that many faculty involved in curriculum reform feel that the benefits provided by alternative instruction (e.g., active learning methods) outweigh the loss of course content, and we support this view.

Still, an ideal pedagogy would not only deeply engage the students in the material, but also successfully introduce and incorporate the principles of a particular discipline. The Case Discussion Method is an active pedagogy that has been used successfully in other disciplines [2–6] to serve this dual purpose. Moreover, the Case Discussion Method provides benefits well beyond these primary requirements. Through the dissection and analysis of real-world dilemmas, students develop higher order functions such as critical-thinking, analytical-reasoning, collaboration, and discussion skills [7]. When students are actively involved in analyzing data, making judgments, and formulating conclusions, they are not only learning basic scientific principles, they are learning the scientific process itself [1].

The Case Discussion Method is a pedagogy that is defined both by a style of written materials—cases—and by the method of using these materials in the classroom to generate interactive student-centered discussions. Cases are factually-based complex dilemmas written to stimulate collaborative analysis and decision making. As a rule, the problems presented in cases do not have a single correct answer; rather, judgments are needed and many possible solutions can be generated. Real-world situations are necessary to cases—they must be important to students and provoke students to actively take part in the discussion and analysis process. Typically, written cases include the background and data pertinent to a particular dilemma, but they do not include the analysis of the data or problem solving strategies. Instead, they are used as vehicles for class discussions. Case discussions also have distinct characteristics that

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designate the case method pedagogy. Facilitated by the instructor, case discussions have a purpose and a direction. Students collectively strive to understand the problem before them and grasp the interrelatedness of the issues. Student interpretation of the dilemma drives the discourse, and the class must formulate a strategy for addressing the problem. The available data must be analyzed, and the class must work toward generating defensible solutions to the complex problem based on data in the case. Throughout this process, the students present their points, question each other, and communicate the basis for their judgments. It is the combination of written cases and case discussions that simulates real-world problem-solving tactics, and promotes the use of the Case Discussion Method pedagogy in many fields [7].

In leading case discussions, the instructor’s role is that of a facilitator, not an authoritarian. Initially, the instructor will distribute the written case to students, often along with some preliminary assignment to help guide their initial reading and digestion of the case. Possible assignments include answering specific questions, doing background research, doing preliminary analysis of the data, or writing thought papers. During a subsequent class meeting, the instructor will initiate the class discussion by asking a few probing questions that allow students to communicate the scope of the dilemma from their perspective. Focused subtly by the instructor, a class discussion ensues in which the students are encouraged to pose questions directly to each other and to share their insights and responses to the case. As the discussion proceeds, the instructor can carefully guide the discussion in light of the teaching objectives for the session. The students can also call upon the instructor for aid in setting up the data analysis or other key fundamental concepts. As the class involvement increases, the instructor’s role becomes more superfluous as the students assume a greater control of the pace and tone of the discussion and move towards formulating their own unique conclusions. In contrast to small group work, the instructor is able to ensure that the entire group of students progresses through the analysis process and examines the fundamental course principles with equal depth.

In general, cases fall into one of two broad categories: prospective and retrospective. Both involve real-world contexts with which students can identify. Retrospective cases are often historical in nature and tell the whole story of a situation including the outcome. The discussion questions in retrospective cases are often along the lines of “Why did it happen?” or “How could it be done differently?” Prospective cases unfold the realistic situation from the viewpoint of a protagonist who ultimately is faced with

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making a decision. These decision-forcing cases can also be historical, but the outcome is not reported. In both types of cases, the situation presented is complex: several points of view or facets related to the central problem are presented. As a consequence, a variety of decisions are defensible and judgments necessarily arise. Regardless of the nature of the case (prospective or retrospective), it must contain a factual or at least realistic scenario that students will find interest-provoking. It is also suggested that cases involve a character with whom students can empathize, as this is found to draw them into deeper involvement with the case [7, 8].

The Case Discussion Method has been used successfully over the past several years in a number of disciplines at both the graduate and undergraduate levels [2–6]. Graduate programs in medicine, law, and business use this method predominantly in their programs with great success. Besides teaching key principles, the Case Discussion Method gives students a broader context in which to understand the material. It builds critical-thinking skills, and develops collaboration and communication skills. The Case Discussion Method is especially effective in honing analytical-reasoning and decision-making skills. Most importantly, the Case Discussion Method is an active pedagogy that creates a dynamic atmosphere in the classroom where students take responsibility for their own learning. In addition, the discussion process that occurs in the classroom provides students with an accurate portrayal of the problem-solving processes utilized in various professions [1, 7].

While the use of the case method in the sciences has been minimal, it has been gaining popularity in recent years [1, 9–14]. A recent article by Coppola [15] describes a program at the University of Michigan in which incoming graduate students are trained to be teaching assistants largely through the use of cases based on ethical dilemmas typically encountered by TAs. The integration of ethical dilemmas into the chemistry curriculum by Coppola and others [16] demonstrates that the Case Discussion Method is gaining acceptance in the sciences. We believe that the Case Discussion Method has much to offer chemistry curricula, particularly at the introductory level. The development of the Case Discussion Method as a vehicle for teaching chemical principles, however, is progressing slowly [17]. One obstacle to the widespread use of cases to teach chemical principles is the lack of available cases that focus on a chemical aspect of an interesting real-world problem. We include in this article an example of a case that incorporates electrochemistry, which we wrote for use in a general chemistry course. We invite others to use this case and we eagerly await to hear about their experiences with both this case and the Case Discussion Method.

Introduction to the “Hommers Mining Dilemma” Case

As an example of the use of this pedagogy, we would like to provide the reader with a case designed to teach chemical principles in an introductory chemistry class. Hommers Mining Dilemma was written for students with minimal discussion and analysis skills and was used in second semester general chemistry classes at St. Olaf College, each of which had 55–60 students. Our goal in writing this case was two fold: (i) to introduce a more active pedagogy to a class otherwise dominated by a lecture format and (ii) to provide students with a broader, realistic context for the basic electrochemical principles. This last point was especially important, as the first sixty percent of the course at St. Olaf develops the principles of chemical thermodynamics from a statistical mechanics basis, with only sparse references to real-world situations. While the case was written specifically to fit into the curriculum at St. Olaf, it is broad enough in scope to be used in any introductory chemistry class, environmental chemistry class, or upper-level analytical or physical chemistry class.

At the point in the semester when we used the Hommers case, the students had already had an introduction to spontaneity, free energy, and electrochemistry. In particular, they could already balance redox equations and calculate ΔG^{o} values from thermodynamic data. Through the use of Hommers, we wanted to (i) practice finding overall cell potentials for various electrochemical reactions, (ii) examine the relationship between the sign of E (cell potential) and thermodynamic spontaneity, and (iii) introduce the dependence of E on temperature, as free energy was shown to be dependent upon temperature.

Note that the Hommers Mining Dilemma demonstrates the great adaptability of the Case Discussion Method, as there are many angles that an instructor in a different course or at a different point in the semester could choose to pursue. For instance, the instructor can emphasize the electrochemical cell on which Melissa is working, the environmental impacts of pyrometallurgy and hydrometallurgy, the economic impact of the mining industry on the community, or the geology of copper rich ores, depending on the students, the course, and instructor expertise.

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Hommers Mining Dilemma

The Hommers Mining Company was at its most critical juncture in its five-year history. The copper mines that had been the mainstay of the company were all but depleted of ore and it looked like the company would have to close its doors in the sleepy town of Caseville, Wisconsin, where it had become one of the chief employers. Although a rich source of copper was known to exist on another part of company land, it was a different kind of copper ore.

The new copper source was composed primarily of the ore chalcopyrite ($CuFeS_2$), rather than tenorite (CuO), which had been the mainstay for Hommers Mining. It would not be possible to reclaim the copper from the new ore by the hydrometallurgical methods used previously. Instead, a pyrometallurgical smelting process would have to be carried out locally to ensure any profit. Smelting is well known to be one of the main sources of atmospheric SO_2, which is one of the precursors to acid rain. In addition, the smelting process emits heavy metals, which are present as sulfides in the ore, into the atmosphere. The citizens of Caseville feared the environmental impact that smelting would have on the health of their families, the nearby lakes, and the land.

Hommers Mining was founded by Melissa Stone, John Gangue, and Henry Coke five years ago. Henry, an experienced miner from Arizona, had come to Wisconsin in search of a small mining company where he could exercise more responsible control of the environmental impacts resulting from the mining operation. In Arizona, where he was just another cog in a gigantic wheel, he was not able to affect company policy much. Time and time again Henry had attempted to instigate a program in land reclamation, but the company was simply not interested.

In Caseville, Henry met John and Melissa who were working in the local gravel mining industry. John was the operations supervisor and Melissa was the laboratory supervisor. John and Melissa shared Henry’s entrepreneurial spirit as well as his concern about the environment. They enthusiastically formed Hommers Mining Company and applied to the town of Caseville for permission to mine the ore deposit. Caseville citizens were cautious, but agreed when they learned of the company’s proposal to allocate 15% of their budget to ensure adequate resources for land reclamation after the ore was depleted. The future of Hommers seemed assured when

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another small business started up in a nearby town that manufactured photovoltaic cells, relying on the Hommers Mining Company for the copper it needed for wiring.

Henry Coke refused to believe that the difficulties in switching from hydrometallurgical processes to the pyrometallurgical process required by the new ore would mean the end of the Hommers Mining Company. He knew that the Wisconsin legislature mandated that all smelting operations reduce the mass ratio of sulfur dioxide emission to metal production to less than one. The operating smelter in Arizona, where the regulations were less strict, recovered 60,000 tons of metal each year while emitting 320,000 tons of SO_2 from its smokestacks. He was sure there was a way to somehow do better than this and even to exceed the standards imposed by law. He wanted to prove to the town that the company was at least as concerned about the environment as the citizens. He just wasn't sure how! After a brief meeting, John was given the task of studying the existing smelting operations, looking for ways to reduce SO_2 emissions. Melissa set to work studying the oxidation-reduction reactions that are the heart of pyrometallurgy to see if there were any improvements that could be made to the refining process. Henry knew that many processes are economical only if the waste products can be turned into useful items, so he set about learning what the markets would be for the iron and sulfur by-products.

John found that there were ways to reduce the SO_2 emissions from the smelting process, but that they were expensive. One method involved neutralizing the acidic stack gases by passing them over a bed of limestone, but this created a large amount of waste product that raised environmental issues of its own. The second method collected the SO_2 emissions and reacted them with water and oxygen in air, forming sulfuric acid which could be sold, although not for any significant profit. In both cases, the capital costs were high, though emissions would be much below the mandated levels. John, however found that there was no existing technology to prevent heavy metal emission from the stacks, so he wasn't sure he could promote these methods. He began to wonder if there was an electrochemical method to remove the heavy metals from the gases.

Henry found that the local demand for the possible iron and sulfur by-products was quite low. Although lots of iron and sulfur are used in steel for construction and in sulfuric acid for chemical manufacturing, both are also already produced in large quantities by other processes. There was some interest in using the sulfur for

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manufacturing lithium sulfide batteries at some point in the future by the solar company, but the demand would not produce much revenue for some time to come.

Melissa began her work by examining the pyrometallurgical process of copper refining. Melissa knew that copper is freed from chalcopyrite in the roasting process when the sulfur is oxidized to form SO_2. She had an idea—but it was a long shot. Instead of roasting the copper ore at 1200 ºC in air and allowing the sulfur by-products to go up a chimney, was there some electrochemical cell that could be constructed that would allow Cu to be separated from its ore when it was in the molten state? It might be possible to design an electrochemical reactor that could contain the reaction by-products much more efficiently and cheaply, making the whole reclamation process much more environmentally sound than the industry standard high-air-flow roasting process. Other metals such as aluminum and sodium were obtained from electrochemical cells using molten materials, but both of these processes required the use of electrolytic cells. In particular, Melissa needed to know if the overall copper reduction process was spontaneous at 950 ºC, the melting point of chalcopyrite, so that electricity wouldn't be needed to drive the reaction. She knew that reduction potentials had a dependence on temperature, and she suspected that deviations from the standard electrochemical potentials would be significant at such high temperatures. If the copper reduction process was spontaneous at the melting point of chalcopyrite, she would make the case to the others that there was a possible alternative to smelting that might allow for better control of emissions of all kinds, heavy metals included. Even if she could demonstrate the feasibility of an electrochemical process to the others, she knew that engineering a new process would involve a great outlay of money and time and would be quite risky. Still, she set about collecting the standard reference data she thought she'd need (Table 1).

As the deadline for their meeting approached; Henry, John, and Melissa were tense. They knew they would have to reach a decision today, for they had to prepare a press release the very next day detailing their plan of action for the Hommers Mining Company. The citizens of the town as well as their employees and the dependent sister company all had something at stake and could wait no longer. Henry began the meeting, "Friends, let's remember why we started this company and focus on where this company is headed...."

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TABLE 1. The Temperature Dependence of a Standard Reduction Potential: $E = E_o + a(T – 298\ \mathrm{K})$.

Half-Reaction	E_o (V versus SHE) [18]	a(mV Versus SHE K^{-1}) [18]
$\frac{1}{2} O_2 + 2H^+ + 2e^- \rightleftharpoons H_2O$	1.2291	-0.8456
$Hg^{2+} + 2e^- \rightleftharpoons Hg(s)$	0.796	-0.327
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	0.771	1.175
$SO_2 + 4H^+ + 4e^- \rightleftharpoons S(s) + 2H_2O$	0.450	-0.652
$Cu^{2+} + 2e^- \rightleftharpoons Cu(s)$	0.337	0.011
$S(s) + 2H^+ + 2e^- \rightleftharpoons H_2S$	0.174	0.224
$Ni^{2+} + 2e^- \rightleftharpoons Ni(s)$	0.337	0.146
$Cd^{2+} + 2e^- \rightleftharpoons Cd(s)$	-0.402	-0.029
$Fe^{2+} + 2e^- \rightleftharpoons Fe(s)$	-0.4402	0.07

Case Teaching Note: Hommers Mining Dilemma

Objectives

Our learning goals for our students for the class period in which we used this case were:

1. to see the usefulness of a spontaneous chemical reaction.
2. to learn how to determine if an electrochemical reaction is spontaneous at various temperatures.
3. to see the relationship between a chemical process and the real-world.
4. to learn the difference between pyrometallurgy and hydrometallurgy.
5. to introduce the interrelatedness of chemical decisions and environmental and economic issues.

Synopsis

A mining company in northern Wisconsin is faced with a dilemma. The copper ore that they have been mining is nearly depleted and the other ore on their site is of a fundamentally different type. This ore will require pyrometallurgical refining, as

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opposed to the hydrometallurgical processing that has been done with the other ore. The company founders explore possibilities of processing the ore on site, cognizant of the environmental harm which may be inflicted. Because they are highly committed to preserving the environment, they explore options which minimize the environmental effects of refining. They must decide which course they will follow, and their decision will be made public in a press release scheduled to appear in the next day's news.

Use of the Case

This case was written for a second semester general chemistry class, as described above. The classes in which this case was used had 55–60 students and met for 55 minutes three times a week. By focusing the class on the electrochemical principles inherent in the case, it was possible to complete an analysis of the spontaneity of the electrochemical process at 950 ºC during one class period. After setting up the calculations together, the class was split up into small groups and students worked through different portions of the analysis involving the data in Table 1, as it applied to Melissa's idea. After a 5–10 minute work period calculating E for the pertinent reactions, we called the class back together and answered the "Is it feasible?" question. Many other plans of action are also likely to be successful as well. The case could cover two or more class periods, with the first period being used to introduce the case, elucidate the basic dilemma, and decide on a course of analysis. Much of the analysis could be performed by students working in small groups in or out of the classroom or students working individually outside of class. Students could also be assigned the task of researching the hydrometallurgical and pyrometallurgical processes for further discussion. Subsequent classes could be used to summarize the electrochemical findings, examine the environmental issues in more detail, and sketch out an in-depth plan for the Hommers Mining Company. Additionally, a laboratory exercise dealing with the electrochemistry of copper, galvanic versus electrolytic cells, or the temperature dependence of cell potentials could accompany this case. The case could also be shortened or simplified by handing out the temperature-dependent values of the cell potentials (Tables 2 and 3 shown in "Is Melissa's idea feasible?" section) and having the class evaluate the overall cell potentials from that point instead.

This case could also be used in an environmental, analytical, or physical chemistry course. In these courses the instructor could choose to emphasize a different aspect of the case. In environmental chemistry classes, for instance, the instructor might focus on smelting as an origin of the acid rain precursor, the nature and effects of heavy

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metal contamination, strip mining versus shaft mining, land reclamation, mine runoff, and a comparison of hydrometallurgy and pyrometallurgy. In an upper-level analytical or physical chemistry class, the students could be expected to progress through the analysis more rapidly with little assistance. The class could focus on the outcome of their decision on the surrounding town and businesses and on the mining industry itself. A physical chemistry class might do the whole analysis in terms of free energy, while an analytical course might stick solely to the use of cell potentials. With some adaptation, this case could also be used in introductory geology or environmental science courses. Topics to focus on for these courses include the environmental consequences of ore removal from the earth and the regional nature of ore deposits. While the case as written clearly leads to an analysis of the electrochemical processes occurring, a class could also analyze the costs involved in the metallurgical procedures. Students could determine the costs involved with some aspects of the various processes, such as creating molten chalcopyrite, electrorefining copper from the impure copper created by smelting or by Melissa's galvanic cell, removing acid rain precursors from the stack emissions, and collecting the emissions and selling them as H_2SO_4. The economic analysis of an electrolytic approach could also be performed. If an external power source was used to bring about the copper reduction (contrary to Melissa's galvanic cell approach), students could obtain local electricity costs and estimate the amount of electricity required to produce the amount of copper in a penny.

Class Plan

In the class, we begin by summarizing the dilemma facing Hommers, and exploring the persona of the company as described in the case. The social and environmental issues are then brought forward and discussed. Because our focus for this case was the chemical principles involved in pyrometallurgy and electrochemistry, we raised questions regarding the social and environmental issues but did not discuss them at length. Students often contribute their views on mining based on personal observations of mines near their homes.

The fundamental chemical issues are then explored. What is the form of the new ore? What is hydrometallurgy? What is pyrometallurgy? The conversation then turns to looking at the individuals in the Hommers organization and examining their roles and findings. While these topics could be discussed in any order, our goal was to arrive at Melissa's idea with ample time left in the class period for the in-depth analysis of the electrochemical data. The students must first, however, have gleaned a picture of what

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the company stands to gain if Melissa's idea shows promise, or they will get too caught up in the calculations and be unable to refocus on the problems facing the company.

Teaching
Themes to keep in mind are: environmental effects, social impact, chemistry, economics (profit), environmental conscience of Hommers.

Questions for participant preparation

In preparation for the class, the students read the case and answered the following questions.

1. What are the important issues to the founders of Hommers Mining?

2. What is the difference between pyrometallurgy and hydrometallurgy?

3. What is the necessary condition for thermodynamic feasibility?

4. What are the environmental consequences of emitting SO_2 into the atmosphere?

5. What do you think the people of Caseville would like Hommers to do?

We intended these questions to be thought provoking for the students. Some of the information necessary to answer the questions is available in the case, some is found in the course textbook, some are judgment calls. Dividing the class and assigning particular research topics prior to doing the case in class would stimulate early exchanges in the case discussion.

If desired, the students could be required to do background reading into pyrometallurgical or hydrometallurgical processing. Our students had a chapter called "Metals and Metallurgy" in their textbook [19] that also provided some of the mining basics. Briefly, the method used in processing copper ores is determined by the nature of the mineral. Hyydrometallurgical methods are applied when processing nonsulfide ores, such as tenorite. Under these conditions the ore is piled in a "heap" and the copper is extracted by spraying dilute sulfuric acid on the heap. The resulting leachate solution must be purified in a solvent extraction step before plating the copper electrochemically (electrowinning). In general, sulfidic ores, such as chalcopyrite, are refined via pyrometallurgical methods because they do not dissolve readily in the sulfuric acid solution. The copper metal in these materials is reduced via smelting and the resulting impure copper is electrorefined. An excellent source on copper mining is *Extractive Metallurgy of Copper* by A. K. Biswas and W. G. Davenport [20].

Questions to use in class:
These are some example questions that could be used in facilitating this case. They may be used in any order.

Exposition of the Dilemma Questions: (Information seeking, opinion forming)

What is Hommers Problem?

What is the history of Hommers Mining Company?

Do you think Hommers really cares about the environment? How do you know?

Where do you think the town stands on the issue?

What are the tasks for company management?

What are the social issues?

What are the environmental issues?

What are heavy metals?

What happens if people ingest heavy metals?

Introduction to Analysis Questions:

What are the chemical issues?

What are the oxidation states of Cu in $CuFeS_2$, CuO, Cu?

What is the fundamental difference between the two ore bodies?

How can Cu be refined?

What is the difference between pyrometallurgy and hydrometallurgy?

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What is John’s conclusion about collection of the stack gases from smelting?

Open-ended Questions:

Why must smelting be done locally to ensure a profit?

What environmental problems are associated with hydrometallurgy and pyrometallurgy?

What is the impact of the company closing or remaining open?

What would Hommers do if and when it ceased the active mining operations?

Who stands to lose or gain if Hommers goes out of the active mining business?

Would any part of the existing facility be usable in pyrometallurgical refining? In Melissa’s scheme?

What kind of image does Hommers want to maintain? What challenges does Hommers face in order to maintain this image?

What are the short term and long term goals of the Hommers Mining Company?

What are the next steps in Melissa’s plan?

What risks are associated with developing Melissa’s process?

Analysis Provoking Questions:

What is Melissa’s idea?

What are the payoffs if Melissa’s idea works?

What is her hope for an alternative process?

Analysis

How does the Arizona smelter measure up under Wisconsin law?

The ratio of SO_2 produced to metal recovered at the Arizona smelter is 320,000 tons of SO_2 per 60,000 tons of Cu, or 5.3. In Wisconsin, this smelter is a far cry from the mandated levels. This analysis can be taken further by looking at the stoichiometry of chalcopyrite. Based on the formula $CuFeS_2$, there would be two moles of SO_2 produced for each mole of Cu. The molecular weights of Cu (63.55 g mol^{-1}) and SO_2 (64.00 g mol^{-1}) being nearly equal, mandates that the stoichiometric ratio of SO_2 produced to metal recovered is 2.0. In order to smelt chalcopyrite and operate within the limit, at least half of the SO_2 coming from chalcopyrite has to be prevented from release through the smokestacks. This is actually a best-case estimate, as the ore is probably not pure chalcopyrite, but contains other sulfidic components that would add to the SO_2 being released, but not to the Cu metal production.

Is Melissa's idea feasible?

As we used this case, the analysis of Melissa's proposition was the center of our discussion. Because our students had just completed discussing the temperature dependence of Gibb's Free Energy, the temperature dependence of electrochemical potential was a natural extension. The students had to determine what the redox reaction(s) involved in Melissa's process were and determine whether the process was thermodynamically feasible at the proposed lower temperature of 950º C. As a group, and with some assistance from the instructor, the class decided upon the appropriate reactions and broke down the full analysis into smaller steps. The class was then briefly divided into small sections, with each section tackling the temperature dependence of a particular half reaction. The results were tabulated on the blackboard, and the overall cell potentials were determined for various redox combinations.

The reaction of interest is the reduction of Cu^{2+} to Cu. This reduction is coupled to the sulfide oxidation: $2\,H_2O + H_2S \rightarrow SO_2 + 6\,H^+ + 6e^-$. Although the sulfide species present in chalcopyrite is not hydrogen sulfide, we introduced the idea of approximation using available information. Combining the two sulfur half-reactions in Table 1, we obtain the desired half-reaction that describes the fate of the sulfur, as shown in Table 2. Instructors could choose to eliminate this step of the analysis by providing data directly in Table 1 for the resultant reaction in Table 2.

The temperature under consideration in Melissa's plan is 950 ºC, 250 ºC lower than 1200 C, the conventional temperature for smelting. Standard electrode potentials reported at 25 ºC are significantly different than the reduction potentials at elevated temperatures. For the instructor's use (or possibly for use in an environmental

TABLE 2. Sulfide/Sulfer Dioxide Half-Reaction.

	E(V versus SHE)		
Reaction	25 °C	950 °C	1200 °C
$SO_2 + 4H^+ + 4e^- \rightleftharpoons S(s) + 2H_2O$	0.450	-0.153	-0.316
$S(s) + 2H^+ + 2e^- \rightleftharpoons H_2S$	0.174	0. 381	0.437
$SO_2 + 6H^+ + 6e^- \rightleftharpoons H_2S + 2H_2O$	0.624	0.228	0.121

TABLE 3. Temperature Dependence of Metal-Containing Half-Reactions.

	E(V versus SHE)		
Half-Reactions	25 °C	950 °C	1200 °C
$Hg^{2+} + 2e^- \rightleftharpoons Hg(s)$	0.796	0.494	0.412
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	0.771	1.858	2.151
$Cu^{2+} + 2e^- \rightleftharpoons Cu(s)$	0.337	0.347	0.350
$Pb^{2+} + 2e^- \rightleftharpoons Pb(s)$	-0.126	-0.491	-0.590
$Ni^{2+} + 2e^- \rightleftharpoons Ni(s)$	-0.236	-0.101	-0.064
$Cd^{2+} + 2e^- \rightleftharpoons Cd(s)$	-0.402	-0.429	-0.436
$Fe^{2+} + 2e^- \rightleftharpoons Fe(s)$	-0.4402	-0.375	-0.358
$Zn^{2+} + 2e^- \rightleftharpoons Zn(s)$	-0.762	-0.652	-0.622

chemistry, environmental science, or geology course) the electrode potentials at 25 ºC, 950 ºC, and 1200 ºC for the half-reactions of the metal ions are listed in Table 3.

By combining the sulfide oxidation half-reaction found in Table 2 with the desired copper reduction reaction listed in Table 3, we can carry out Melissa's analysis and determine if the overall copper reduction process will occur spontaneously. This analysis is shown in Table 4. The calculated electrochemical potential for these coupled reactions at 950 ºC is +0.119 V (see entry in Table 4), corresponding to

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TABLE 4. Combination of Sulfide Oxidation with Copper Reduction.

Reaction	E(V versus SHE) 25 °C	950 °C	1200 °C	ΔG (kJ mol^{-1}) 950 °C	1200 °C
$H_2S + 2H_2O \rightleftharpoons SO_2 + 6H^+ + 6e^-$	-0.624	-0.228	-0.121		
$Cu^{2+} + 2e^- \rightleftharpoons Cu$	0.337	0.347	0.350		
$3Cu^{2+} + H_2S + 2H_2O \rightleftharpoons 3Cu + SO_2 + 6H^+$	-0.287	0.119	0.229	-67.7	-130.3

TABLE 5. Combination of Sulfide Oxidation with Metal Reduction.

Half-Reaction Coupled to Sulfide Oxidation:	E(V versus SHE) 25 °C	950 °C	1200 °C	ΔG (kJ mol^{-1}) 950 °C	1200 °C
$Hg^{2+} + 2e^- \rightleftharpoons Hg(l)$	0.172	0.265	0.291	-153.6	-168.3
$Fe^{3+} + e^- \rightleftharpoons Fe^{2+}$	0.147	1.630	2.030	-943.6	-1195.0
$Pb^{2+} + 2e^- \rightleftharpoons Pb(s)$	-0.750	-0.719	-0.711	416.5	411.7
$Ni^{2+} + 2e^- \rightleftharpoons Ni(s)$	-0.860	-0.329	-0.186	190.5	107.5
$Fe^{2+} + 2e^- \rightleftharpoons Fe(s)$	-1.064	-0.604	-0.479	355.5	282.0
$Zn^{2+} + 2e^- \rightleftharpoons Zn(s)$	-1.386	-0.880	-0.743	509.5	430.3
$Cd^{2+} + 2e^- \rightleftharpoons Cd(s)$	-1.026	-0.657	-0.557	380.3	322.6

ΔG = -67.7 kJ mol^{-1}, a spontaneous process. From Table 4, it is clear that the process is also spontaneous at 1200 ºC, as expected since this is the temperature at which smelting is normally carried out. It is not spontaneous at room temperature, consistent with experience.

Variations on the analysis can arise if students examine the fate of other metals (possible toxic impurities) in the ore. Table 5 lists the electrode potentials obtained by coupling the sulfur oxidation reaction (Table 2) with the half-reactions listed in Table 5. The only two metals of those listed that are spontaneously reduced by H_2S at either 950 °C or 1200 °C are Hg^{2+} and Fe^{3+}. Still, the students can get somewhat

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bogged down in what happens to the other metals—it might be helpful to try and focus attention merely on the Cu reduction/S oxidation because this is the crux of Melissa's idea. Advanced classes could be asked to examine these alternative processes in more detail as a take-home exercise.

Electrolytic Cell: A cost analysis.

The above analysis shows that thermodynamically Cu can be spontaneously obtained from chalcopyrite in its molten state. It might also be desirable to examine the energy required to reduce copper in an electrolytic cell, in the event that a galvanic cell cannot be constructed. In any event, this type of calculation is often included in a presentation of electrochemical principles and is included here for the benefit of others who may use this case. A useful problem is to determine the cost of reducing the amount of copper found in a penny and compare it to the worth of the penny. First, determine the number of coulombs required to generate one mole of copper metal (63.55 g mol^{-1}).

$$\#\mathit{coulombs} = (63.55\text{ g})\left(\frac{1\text{ mol Cu}}{63.55\text{ g}}\right)\left(\frac{2\text{ mol e}^-}{1\text{ mol Cu}}\right)\left(\frac{96500\text{ C}}{1\text{ mol e}^-}\right) = 1.93\times10^5\text{C}$$

Power companies typically deal with units of kilowatt hours (kWh). A kilowatt watt hour can also be expressed in joules: 1 kWh = 3.60 × 10^6 J. The number of kWh needed to produce one mole of copper can be obtained, assuming that the electrolytic cell is run at a potential of 2.00 V.

$$\#\text{kWh} = \left(1.93\ \times\ 10^5\ \text{C}\right)(2.00\text{ V})\left(\frac{\text{J}}{\text{V}\times\text{C}}\right)\left(\frac{1\text{ kWh}}{3.6\ \times\ 10^6\ \text{J}}\right) = 0.107\text{ kWh}$$

If the process is assumed to be only 40% efficient, then 0.268 kWh of energy is needed to produce 63.55 g Cu. If a penny weights 3.12 g, then 0.0132 kWh is needed to produce the copper for one penny. At 0.7¢ per kWh [21], it would cost 0.0092¢ to make a penny. Note that this does not include the cost of heating the ore to its molten state, nor does it include the cost of mining the ore, casting the penny, further refining the copper, and many other steps.

After completing the analysis of the electrochemical data, if time allows, the class could convene a town meeting where students took on roles of Melissa, Henry, John,

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the Mayor of Caseville, a lifelong resident of Caseville, and other citizens. In a role-playing mode, the various plans and strategies could be brought forth and examined.

Follow up questions

The students submitted their answers to these questions as homework following the case class:

1. What was the most important issue raised during the case?
2. What was the most important chemical concept learned or used during the case?
3. What did you learn from the discussion that you did not learn from the reading?
4. What is the redox reaction for separating Cu from $CuFeS_2$? Determine E and ΔG for this reaction at 25 °C, at 950 °C, and at 1200 °C.
5. Write the press release that Hommers releases to the media. Be sure to include the plan they have decided upon for Hommers and their justification for their choice.

The first three questions were especially enlightening to the students. They found that their typical textbook reading merely skimmed the surface of the concepts in the case and that a more careful, critical reading of the case was required in preparation for the discussion. The fourth question got at the heart of the chemical principles that we hoped to cover. The fifth question appeared to need more background, as many of our first-year students were unfamiliar with press releases.

Comments on flow of discussion.

1. Some students were fixated on the iron and wanted to know what happened to it. That was not the focus of the case and some efforts to steer the attention away from iron were needed. In the smelting process iron participates in several reactions, but ultimately ends up as magnetite (Fe_3O_4).

2. Time is a problem if the group does not move efficiently to the analysis of the electrochemical data, if that is the desired goal. The full analysis of the temperature-dependent electrochemical data (including but not limited to the

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calculations) can take 20–30 minutes, and the students are likely to need coaching to get started.

3. In environmental classes, allow more time for the environmental and social issues to be explored. Some analysis could be done out of class or many of the outcomes reported more directly leaving a less cumbersome analysis for the class period.

4. Because our intention was to teach content with this case, we did not extensively explore the environmental, social, and economic aspects of this case in a 55-minute class period. If both the chemical principles and the other aspects were going to be discussed, a longer class period, or several class periods, would be more suitable.

5. Students may have difficulty grasping the idea that Melissa's ideas may be thermodynamically favorable, but still not feasible from a technological point of view. Additionally, the kinetics of the process have yet to be considered. The cost of researching and developing a new process should also be mentioned.

Conclusions

We believe that the Case Discussion Method pedagogy could strongly impact introductory chemistry classes by providing students with both a real-world context for the chemical principles and a more accurate portrayal of the way that modern science is practiced. The collaborative nature of the Case Discussion Method removes the competitive attitude that often surfaces in introductory chemistry courses and thereby creates a better working atmosphere for all students. We have also found that the Case Discussion Method brings students from a variety of backgrounds to the same level of class involvement, which is especially important in classes that include both students who have taken Advanced Placement chemistry and those who have not taken chemistry previously. Most importantly, by simulating the scientific problem-solving process in the classroom, students gain an understanding of what it means to think like a chemist and gain confidence in their ability to carry out those thought processes. The Case Discussion Method is an ideal pedagogy for demonstrating to students the interaction of science, technology, and society, and it allows them to develop a sense of the social impact of science-related decisions.

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REFERENCES

1. Herreid, C. F. "Case Studies in Science - A Novel Method of Science Education" *J. College Science Teaching* **1994**, 221.

2. The case method of teaching was developed at the Harvard Business School. It is also used extensively in medical schools, business schools, law schools, and schools of public policy. For example, the Kennedy School of Government has a substantial case program that can be contacted at Case Program Sales Office, Kennedy School of Government, Harvard University, 79 John F. Kennedy Street, Cambridge, MA 02138.

3. Case Program at the Economic Development Institute of the World Bank; http://www.worldbank.org/html/edi/cases/caseindex.html; Vinod Thomas, EDI Director, Washington DC.

4. Program for Decision Cases; http://www.decisioncase.edu; University of Minnesota, College of Agriculture, 411 Borlaug Hall, St. Paul, MN 55108-6026; email:dunru001@gold.tc.umn.edu.

5. Leuner, J. D.; Manton, A. K.; Kelliher, D. B.; Sullivan, S. P.; Doherty, M. *Mastering the Nursing Process: A Case Method Approach*; F.A. Davis Co.: Philadelphia, 1990.

6. Zeigler, E. F. *Decision-Making in Physical Education and Athletics Administration: A Case Method Approach*; Stipes Publishing Co.: Champaign, IL, 1982.

7. Boehrer, J.; Linsky, M. "Teaching with Cases: Learning to Question" New Directions for Teaching and Learning, No. 42; Jossey-Bass, Inc.: San Francisco, CA, 1990.

8. Robyn, D. "What Makes a Good Case?" © President and Fellows of Harvard College, **1985**, No. N15-86-673.0.

9. James Bryant Conant used the case method to teach chemistry. His method is described in *On Understanding Science*; Yale University Press: New Haven, 1947. A collection of seven historically based cases can be found in Conant, J. B.; Nash, L. K.; Roller, D.; Roller D. H. D. *Harvard Case Histories in Experimental Science*; Conant, J. B.; Nash, L. K. Eds. Harvard University Press: Cambridge, MA, 1964; Vol. 1 and 2.

10. Wheatley, J. "The Use of Case Studies in the Science Classroom", *J. College Science Teaching*, **1986**, 428.

ISSN 1430-4171
http://journals.springer-ny.com/chedr
S 1430-4171 (97)06070-6

11. Clerc, J. “Teaching Laboratory Safety: A Case Study” *J. College Science Teaching*, **1996**, 337.

12. Herreid, C. F. “Case Study Teaching in Science: A Dilemma Case on “Animal Rights” *J. College Science Teaching*, **1996**, 413.

13. Herreid, C. F. “Journal Articles as Case Studies - *The New England Journal of Medicine* on Breast Cancer” *J. College Science Teaching*, **1994**, 349.

14. Giunta, C. J. “The Discovery of Argon: a Case Study in Scientific Method” Avail.URL: http://maple.lemoyne.edu/~giunta/acspaper.html. Department of Chemistry, LeMoyne College, Syracuse, NY 13214.

15. Coppola, B. P. *Chem Educator* **1996**, *1(4)*, S1430-4171 (96) 04050-2. Avail. URL: http//jounals.springer-ny.com/chedr.

16. Kovac, J. “Scientific Ethics in Chemical Education” *J. Chem. Educ.* **1996**, *73*, 926. Kovac, J. *The Ethical Chemist*; University of Tennessee Chemistry Department: Knoxville, 1993. Delaware, D. L.; Freeman, R. G.; Moody, A. E.; Van Galen, D. “The Freshman Chemistry Seminar” *J. Chem. Educ.* **1996**, *73*, 144.

17. There are very few published cases that are primarily intended to teach chemical principles. A recent publication does present three cases (Challen, P. R.; Brazdil, L. C. *Chem Educator* **1996**, *1(5)*: S1430-4171 (96) 05056-X, Avail. URL: http://journals.springer-ny.com/chedr). While there are a variety of other group exercises developed recently that teach chemical principles, they do not contain the essential elements of the Case Discussion Method pedagogy. In addition, a recent letter to the editor requested correspondence from other teachers interested in or using the Case Discussion Method in chemistry (Luberoff, B. J.; Peterson, L. I. *C&EN*, June 10, 1996, 2).

18. Harris, D. C. *Quantitative Chemical Analysis*, 3rd ed.; Freeman: New York, 1991.

19. Brown, T. L.; LeMay, H. E., Jr.; Bursten, B. E. *Chemistry: The Central Science*, 6th ed.; Prentice Hall: Englewoods Cliffs, NJ, 1994, Chapter 24.

20. Biswas, A. K.; Davenport, W. G. *Extractive Metallurgy of Copy*, 3rd ed.; Pergammon/Elsevier: Oxford, 1994.

21. The average cost per kWh of electricity in Northfield, MN is 0.7¢.