AC 2010-1889: RESULTS AND ANALYSIS OF A REQUIRED SENIOR EXAM TO ASSESS LEARNING OF COURSE COMPETENCIES.

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Results and Analysis of a Required Senior Exam  
To Assess Learning of Course Competencies.

Abstract

As part of the ABET Accreditation Criterion, Program Outcomes refer to the outcomes that chemical engineering students should possess when they leave the university and enter the workforce. In 1999, as a response to ABET’s EC2000 criterion, a list of specific competencies was defined in the Chemical Engineering Program at Brigham Young University that, when taken together, constituted each Program Outcome. When the competencies were first developed, it became clear that the level of mastery expected from students varied from competency to competency. Exposure to the material was all that was required for some competencies. For others, it was our expectation that students should not graduate without demonstrating a specified level of mastery. The expected level of mastery is intimately connected to the types of practices, assessment, and feedback associated with a given competency. Consequently, a mastery level of 0, 1, 2, or 3 was assigned to each competency.

Level-0, which is described as optional, includes competencies that are desirable, but not required. Level-1 indicates some familiarity and experience, but defines no minimum level of performance. Level-2 includes chemical engineering skills in which students can solve engineering problems with the aid of reference materials. Level-3 competencies focus on fundamental concepts and principles upon which the skills/applications are based. Level-3 competencies provide the foundation for problem solving, and it is expected that students master these competencies sufficiently to solve engineering problems given little or no reference material.

When assigning levels to each competency, we identified 18 of the competencies as Level-3 competencies for assessment prior to graduation using a multiple-choice Level 3 (L3) competency exam. Similar to other competencies, these competencies are assessed at the course level with typical assessments such as homework, quizzes, and/or exams problems. The L3 exam is multiple-choice in format and is geared for approximately two hours. The exam is administered early in the senior year. Successful completion of the L3 exam is required for graduation.

This paper will discuss the results of the L3 exam since its inception as a graduation requirement in 2002. Insights will be discussed regarding pass rates, commonly missed competencies, comparisons between years of administration, and the feedback information to the curriculum. Critical assessment of the L3 exam process since inception will also be presented.

Introduction

In 1999, Program Outcomes at Brigham Young University were established in response to ABET EC2000 requirements. Program Outcomes, as defined by ABET, “are narrower statements that describe what students are expected to know and be able to do by the time of graduation. These relate to the skills, knowledge, and behaviors that students acquire in their
Assessed in courses through the program. Initially, the faculty sought to simply use the ABET-specified Program Outcomes along with some additional outcomes associated with chemical engineering criterion; however, little progress was made using this strategy because there was no sense of ownership of the process. It was then decided to develop a set of Program Outcomes personalized to our program rather than those defined by ABET. This also allowed incorporation of Program Outcomes specific to the mission of Brigham Young University.

Details of the process for developing the Program Outcomes have previously been described. Briefly, the process began by first listing the skills and experiences expected of each student for each semester and course for our entire program. These skills and experiences were labeled “competencies” and represented the specific characteristics that we desired for our students. Similar competencies were grouped together and used to define a Program Outcome that characterized that group of competencies. The net result was a list of twelve Program Outcomes with associated competencies. Each course in our program contains competencies from several Program Outcomes. Each competency has a numerical designation—the first number corresponds to the Program Outcome.

When the competencies were first developed in response to ABET’s EC2000, it became clear that the level of mastery expected from students varied from competency to competency. Exposure to the material was all that was required for some competencies. For others, it was our expectation that students should not graduate without demonstrating a specified level of mastery. The expected level of mastery is intimately connected to the types of practices, assessment, and feedback associated with a given competency. Consequently, four different mastery levels, shown in Table 1, were defined and used to classify the competencies.

Table 1. Description of Competency Mastery Levels

<table>
<thead>
<tr>
<th>Level</th>
<th>Description</th>
<th>Assessment Method</th>
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<tbody>
<tr>
<td>0</td>
<td>Indicates competency is desirable but not required (optional)</td>
<td>Not Assessed</td>
</tr>
<tr>
<td>1</td>
<td>Indicates familiarity and experience</td>
<td>No minimum level of performance required</td>
</tr>
<tr>
<td>2</td>
<td>Indicates skills required to be a qualified chemical engineer</td>
<td>Assessed in courses through assignments, mid-term exams, finals, projects, etc.</td>
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<tr>
<td></td>
<td>(<em>mastered sufficiently to solve engineering problems with the aid of reference materials</em>)</td>
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</tr>
<tr>
<td>3</td>
<td>Indicates fundamental principles providing the foundation for problem solving strategies</td>
<td>Assessed in courses and prior to graduation (on the closed-book L3 exam)</td>
</tr>
<tr>
<td></td>
<td>(<em>mastered sufficiently to solve engineering problems using little or no reference materials</em>)</td>
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Level 0, which is described as optional, includes competencies that are desirable, but not required, such as having an industrial internship. Level 1 indicates some familiarity and experience, but defines no minimum level of performance, such as effective reading of graphical
data. Level 2 includes chemical engineering skills such as determination of pressure drop in a pipe, the number of trays in a distillation column, or the volume of a reactor. Students must be proficient at these competencies to an extent that students can solve engineering problems with the aid of reference materials.

The intent of the Level-3 competencies is to focus on fundamental concepts and principles upon which the skills/applications are based. When a student successfully solves an engineering problem, it is commonly assumed that the underlying fundamental competencies have been mastered. Our experience indicates that students can become adept at applying correlations or procedures to obtain a correct or partially correct solution by simply mimicking a process demonstrated by an instructor or illustrated in a textbook, and that they frequently do this without a firm grasp of the underlying physics, or in other words the fundamental competencies. This acquired problem-solving ability is short lived and limited because it is not founded upon a mastery of the underlying fundamental competencies. When these students are required to apply the competency to the solution of a somewhat different problem, or to apply these competencies after some time has passed, they are frequently at a loss as to how to proceed. They try to remember an equation or correlation and write whatever they are able to retrieve from their memory without thinking through the problem in a manner consistent with a well-founded conceptual understanding.

Level-3 competencies provide the foundation for problem solving. It is expected that students master these competencies sufficiently to solve engineering problems given little or no reference material. Therefore, we identified 18 of the 141 competencies as Level-3 competencies for assessment prior to graduation using a multiple-choice Level 3 (L3) competency exam. The 18 Level-3 competencies are associated with Program Outcome 3 (applying knowledge of chemical engineering fundamentals) and Program Outcome 10 (applying chemical engineering fundamentals to design process units and systems of process units). Similar to other competencies, these competencies are also assessed at the course level with typical assessments such as homework, quizzes, and/or exams problems. Emphasis is given in the department curriculum to practices and assessment methods that are focused on these Level-3 competencies. The goal is to have every student achieve mastery of the Level-3 competencies to the point where their understanding effectively becomes engineering intuition and they can recall and apply the principles using little or no reference material. The focus of this paper is on the L3 exam, which is a multiple choice exam covering 18 of the Level-3 competencies. The paper will specifically discuss the exam results since inception and the associated evaluation and feedback to the program.
L3 Competency Exam

The exam became a mandatory requirement for graduation beginning in 2002 after a pilot program in 2001 and was originally administered on paper. The exam fulfills several important purposes. First, it validates the technical training of every graduate by demonstrating mastery of the Level-3 competencies. Second, it provides feedback to our program on specific competencies and areas where our students may be weak. This feedback provides motivation for curricular and/or pedagogical modifications needed to address the problem(s). Third, the exam emphasizes the importance of the Level-3 competencies to our students and faculty. Students are keenly aware that retention of knowledge and skills in the core areas is a requirement for graduation in addition to simply completing required course work. Faculty awareness of the need to help students learn fundamental concepts is also heightened.

Table 2 shows the 18 Level-3 competencies assessed by the exam. As previously stated, the first number of the competency corresponds to a Program Outcome. As shown, some of the competencies are broken into two or three sublevels for testing. For example, competency 3.1.1, which concerns the ability to use basic engineering units in solving problems and the ability to interconvert between unit systems is divided into two sublevels involving fundamental units such as length and time (Competency 3.1.1.1) and problems involving derived units such as force and pressure (Competency 3.1.1.2). With the addition of sublevels, the 18 competencies are expanded into 24 competency expectations that are assessed on the L3 exam with 24 associated questions. These 24 competency expectations are referred to as 24 competencies in the remaining text. Our experience with a pilot exam indicated that we should allow an average of about five minutes per question—thus the exam is geared for approximately two hours.

Table 2. Competencies covered by Level-3 Competency Exam.

<table>
<thead>
<tr>
<th>Competency</th>
<th>Sublevel</th>
<th>Competency Expectation</th>
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<tbody>
<tr>
<td>3.1.1</td>
<td>3.1.1.1</td>
<td>Students will be able to convert fundamental units and simple combinations of fundamental units between and within the AES and SI systems of units.</td>
</tr>
<tr>
<td>3.1.1</td>
<td>3.1.1.2</td>
<td>Students will be able to convert derived units (e.g., force, pressure, power, etc.) between and within the AES and SI systems of units.</td>
</tr>
<tr>
<td>3.1.2</td>
<td>3.1.2.1</td>
<td>Students will be able to solve steady-state material balances for non-reacting, single-unit systems.</td>
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<tr>
<td>3.1.2</td>
<td>3.1.2.2</td>
<td>Students will be able to solve steady-state energy balances for single-unit, isothermal, reacting systems.</td>
</tr>
<tr>
<td>3.1.2</td>
<td>3.1.2.3</td>
<td>Students will be able to solve steady-state material balances for single-unit, reacting systems.</td>
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<tr>
<td>3.2.1</td>
<td></td>
<td>Students will be able to identify equilibrium phases on either PT or PV projections of the PVT surface, and be able to obtain vapor pressures for pure components for a given temperature.</td>
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<tr>
<td>3.3.1</td>
<td></td>
<td>Students will be able to solve the mechanical energy balance for frictionless flow with and without shaft work.</td>
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<tr>
<td>3.3.2</td>
<td></td>
<td>Students will be able to (1) describe qualitatively the physical significance of viscosity in terms of fluid behavior; (2) define and describe the physical significance of Re; (3) describe flow regimes that correspond to different values of Re.</td>
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<tr>
<td>3.4.1</td>
<td></td>
<td>Students will: (1) be able to assign appropriate modes of HT to a given physical scenario, (2) know Newton’s law of cooling, understand, and be able to use</td>
</tr>
<tr>
<td>Section</td>
<td>Description</td>
<td></td>
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<tr>
<td>3.4.2</td>
<td>Students will understand conduction and convection resistances, and be able to use ( q = \Delta T / \Sigma \text{Res} ) and ( q = UA \Delta T_{in} ).</td>
<td></td>
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<tr>
<td>3.4.3</td>
<td>Students will understand ( q = hA \Delta T ) and how ( h ) is qualitatively related to ( \text{Nu, Re, and Pr} ), and how to obtain a value for ( h ) - qualitative problem.</td>
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<tr>
<td>3.5.1</td>
<td>Students will understand Fick’s law and the contributions to the flux arising from a driving force and from convection.</td>
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<tr>
<td>3.5.2</td>
<td>Students will be able to use the heat/mass transfer analogy to estimate mass transfer coefficients.</td>
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<tr>
<td>3.6.1</td>
<td>Students will understand and be able to use definitions of rate and nth-order rate expressions. They will know how to determine ( n ) from basic rate data.</td>
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<tr>
<td>3.7.1</td>
<td>Students will be able to solve steady-state, first law problems with open, non-reacting, single-process units (e.g., compressors, valves, heat exchangers).</td>
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<tr>
<td>3.7.2</td>
<td>Students will be able to solve first-law problems with single process units for closed systems.</td>
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<tr>
<td>10.1.1</td>
<td>Students will be able to use the design equations for ideal reactors to determine reactor volume, feed flow rate, or conversion.</td>
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<tr>
<td>10.2.1</td>
<td>Students will be able to do preliminary size and performance calculations on shell-and-tube heat exchangers using the log-mean temperature difference method.</td>
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<tr>
<td>10.3.1</td>
<td>Students will be able to determine the power required for a pump to deliver a specified flow rate of an incompressible fluid through a single pipeline (excludes flow in parallel lengths) consisting of pipe (multiple diameters acceptable), valves, and fittings.</td>
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<tr>
<td>10.4.2</td>
<td>Students will be able to use Raoult’s law and vapor pressure correlations to solve the VLE and mass balances associated with a single-stage isothermal flash.</td>
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</table>

Questions on the L3 exam stress conceptual understanding whenever possible rather than the ability to simply plug numbers into an equation. To ensure the quality of the exam and minimize common test-taking errors, questions are prepared and reviewed by faculty teams to ensure that they focus narrowly on the desired competency and are free of typographical or factual errors and ambiguities. Writing good questions is a daunting task, so student performance on each equation is evaluated routinely to identify poorly-constructed questions.

The exam is multiple-choice in format in order to facilitate the generation of a sufficient quantity of questions, permit instant machine-grading of the exams, and facilitate data gathering and processing. The exam resides on a secure server and consists of two parts: 1) a database which contains the questions for the exam and records student performance and 2) code which is used to administer the exam by generating the tests from the bank of questions in the database. The security of the server is taken very seriously. Neither the server nor the client computers upon which the students take the exam are connected to the outside world. The server is housed away from student areas, and the only people with log-in credentials are the department secretary (to
input student information), the department computer support representative, the department chair, and the faculty member in charge of administering the exam.

The database contains several questions (5+, each written by faculty) for each of the 24 competencies. The code to administer the exam was developed “in-house” using server-side scripting. For each exam, the code randomly generates the competency order, the question for each competency, and the answer order of each question. The server logs the question order, questions given, and student responses so that the entire exam and student answers are available should a concern about exam efficacy or accuracy ever arise.

The exam room contains four test-taking computers linked to a server which controls the exam. Security in this room is kept high. Access to the exam room is restricted except during exam times, and the room is constantly monitored by a closed-circuit camera. Students are only allowed to take a calculator and a pencil into the exam room. Scratch paper and an exam booklet containing the allowed reference materials such as conversion factors, steam tables, Antoine Constants, and a Moody diagram are provided. Each booklet and all used scratch paper are shredded upon completion of the exam.

The exam is initially administered during September of the senior year during a 4-day period. Once the students complete the exam, they are immediately given their scores and told which competency (if any) that they did not pass. Then, after a period of about a month, they are given a second exam that includes only questions that address the competencies that were missed on their previous attempt. This exam is automatically generated by the server computer based on the student’s performance on the previous exam and never contains the same questions. A third exam, similar to the second exam, is administered for any competencies that remain “un-mastered” after the second exam. Students must pass 23 of the 24 competencies by the third try in order to pass the exam.

If three tries proves insufficient, the following procedure is used to strengthen student proficiency for each missed competency.

1. The student is notified of a faculty mentor who has been assigned to “guide” the student’s study. A faculty mentor is assigned for each failed competency.
2. It is the responsibility of the student to meet with the faculty mentor and to actively pursue the completion of the requirements. The student should understand that failure to complete the requirements will delay his/her graduation.
3. The faculty mentor assigns the student reading from texts, notes, and other materials specific to the missed competency that the faculty mentor deems appropriate for the student to study. An appropriate number (as determined by the faculty member to cover the breadth of the given competency) of homework problems oriented toward strengthening the competency are also assigned.
4. The student completes the work given by the faculty mentor and discusses the work and what he/she has learned.
5. The student prepares six or more (depending upon the breadth of the competency) L3-style questions of his/her own with correct answers and possible wrong answers. This is reviewed by the faculty mentor.
6. When the faculty mentor is satisfied with the level of mastery by the student, the faculty mentor provides an exam to the student consisting of five L3-style questions. The student takes the exam and must answer at least three of the five questions completely correctly.

7. Students that pass the exam given by the faculty mentor (see previous item) are passed on that competency.

8. Should any student fail the faculty mentor exam (see item 6), the student will be required to retake the L3 exam the next year under the same rules as before (i.e., all 24 questions, 3 tries, pass 23 questions). Note that this will delay graduation possibly by one or more semesters. During this time, the student will likely re-take courses that build the competency/competencies that were missed. Note also that all of the competencies missed on the third try of the L3 exam must be passed by these mentor exams for the student to pass the L3 exam.

L3 Competency Exam Results

Figure 1 shows the cumulative passing rate after each try since the inception of the exam. At this writing students in the 09-10 year have just finished the second try so the third try is not shown. The number of students that took the exam is 72, 54, 50, 32, 52, 56, 53, and 54 for the eight consecutive years shown in the figure. For all of the combined years, an average of 16.3 ± 5.0 % (standard deviation) of the students passed the exam by the first try whereas the average drastically increased to 78.7 ± 7.8 % by the second try. As noted by the trend beginning with 06-07, there has been an increase in the number of students passing the exam by the second try although the current levels are now back to the levels prior to 06-07. Since the exam has been administered, a total of 10 students failed to pass at least 23 competencies by the third try. These 10 followed the makeup procedure previously outlined and all passed the instructor-administered exam. It is not clear as to why more students did not pass the exam on the first try. However, it is important to recognize that students missing just a few competencies (i.e. two or three) were considered as not passing although missing only three competencies would still be a passage rate of 88%.
Using data from the last four years, Figure 2 shows the number of students that missed a given number of competencies following the first try. As previously stated, students missing one or less competencies received a “pass” on the exam. An interesting note to point out is that of the students that did not pass on the first try, 42, 55, 29, and 35% missed only two or three competencies (passing > 88% of competencies) for the 06-07, 07-08, 08-09, and 09-10 years, respectively. These percentages increased to 72, 70, 48, and 40, respectively, for missing between two and four competencies. Thus, it can be seen that a significant number of students are only within a few competencies of passing the exam by the second try. Since the L3 exam is administered over a short time period (two months), passage on the second and third tries due to improved test taking capabilities is unlikely. However, it is possible that students study more following the first try once they are notified of the competencies they did not pass.
The question arises as to which competencies are missed the most since this information could be useful for identifying potential course and/or curriculum changes that could strengthen student learning and retention of these core competencies. Figure 3 shows the average miss rate for each competency for the cumulative years of 2002-2009 for all tries. It is clear that competencies 10.1.1, 3.7.3, and 3.7.1.2 have the greatest miss rates. Since inception of the exam, these three competencies were consistently ranked in the top five in terms of miss rates and are often in the top three. For these competencies, students receive the greatest instruction during the 2nd semester of the junior year in either the chemical reaction engineering course (10.1.1) or the thermodynamics course (3.7.3 and 3.7.1.2). Although not shown, the miss rates were consistent among competencies even when course instructors were changed, suggesting that the reasons for missing the competencies are not specifically related to an instructor. Therefore, we decided to take a more in-depth review of these three competencies to evaluate potential reasons for the high miss rate and to provide recommended feedback to the program to address the student learning and retention of these three competencies.
Figure 3. Average miss rate for each competency during 2002-09.

Evaluation and Feedback

Throughout the years, evaluation of the results involved annually reporting the results to the faculty throughout the first, second, and third tries and discussing trends noted in the above figures. Occasionally, a few L3 exam questions were reviewed and a few changes in the questions occurred, but little evaluation of the results for program improvement was attempted since all students eventually passed the exam, either by passing by the third try or after completing the additional requirements noted above. The 100% pass rate is very commendable and should not be overlooked. However, feedback for program improvement was minimal. Recently, the lack of rigorous evaluation led to the question as to how valuable the L3 exam was for program improvement and student learning, rather than just being another graduation requirement. Since 2008, we decided to make a more rigorous evaluation of the exam results. To be an effective assessment tool, the L3 exam should provide guidance to program improvement and student learning.

As we began a more rigorous evaluation, we decided to focus on the three competencies that were consistently ranked near the highest in terms of miss rates. In order to determine the cause for the high miss rates, the miss rates of the first try for each question related to each of the three
competencies were reviewed and recommendations were provided. The recommendations were communicated to the instructors at the beginning of the winter 2010 semester. Follow-up will occur during the 2010-2011 academic year by comparing the performance on the competency at that time with the previous performance.

**Competency 10.1.1**

This competency states that students will be able to use the design equations for ideal reactors to determine reactor volume, feed flow rate, or conversion. The L3 exam has a total of five questions that cover this competency. The miss rates ranged from 22-56%. After reviewing the missed competencies, it was determined that two questions needed to be reworded since the wording may have caused some confusion—leading to missed competencies. One question regarding CSTR assumptions (22% miss rate) utilized the statement “the entire reactor is isothermal”. However, it was felt that this phrase could be confusing to students since an isothermal reactor can also relate to a reactor with the same inlet and reactor temperature. It was decided to rephrase the statement to “no temperature gradients in the reactor”. A second question (miss rate 33%) inappropriately used the word “initial” instead of “inlet” concentration. This may have confused students since only steady state problems are on the L3 exam. This correction has also occurred. It will be interesting to determine whether the word change alone will decrease the miss rates.

On the other hand, three of the reviewed questions (miss rates of 23-56%) provided strong evidence that students are primarily confusing concentrations at the inlet of the reactor to concentrations within the reactor. During the Winter 2008 offering of the Chemical Reaction Engineering course, a summary sheet that highlighted the material balances for the CSTR and PFR was used to help alleviate this mistake. The summary sheet included the following information:

\[
\text{Steady state CSTR material balance of species A: } 0 = F_{A,in} - F_{A,out} + r_A V
\]

Exams during and at the end of the semester were written to help assess the ability of the students to use the correct concentration in solving CSTR problems. The exam results showed that students did very well in having a proper understanding.

In contrast, several students that completed the Winter 2008 course did not initially pass the 10.1.1 competency for the L3 exam that was given eight months later. It was noted that the information given in the L3 reference booklet, which can be used for the L3 exam, gives a CSTR “performance” equation in the form of \(V/F_{A0} = X_A/\theta_A\). This equation is a combination of the steady state CSTR material balance for species A and the definition of conversion. Rather than using this “performance” equation, it was recommended that the L3 reference booklet remove the “performance” equation and provide the above noted information from the summary sheet as well as the definition of the conversion of A: \(F_{A,out} = F_{A,in} (1 - X_A)\). These recommended changes provide an opportunity for students to be reminded of the material balance in which accumulation = in – out + net generation. Thus, there is an implied emphasis regarding inlet concentrations associated with the inlet term and reactor concentrations associated with the net generation term. The “performance” equation may have provided a disservice to the students.
since it was a rearranged equation that encouraged memorization rather than understanding. Future results will enable an assessment as to whether the above recommended equations trigger a reminder that the inlet information is only associated with the inlet term.

Competency 3.7.3

This competency states that students will know how $\Delta G$ is related to equilibrium constants and will be able to calculate an equilibrium constant (from $\Delta G^o$) at 298 K and relate equilibrium constants to the extent of reaction for ideal gas phase reactions. The L3 exam has a total of six questions that cover this competency. The miss rates ranged from 30-69%. There are basically two skills involved in this competency. The first skill, which is covered by two questions, involves converting between $K$ and $\Delta G^o$. This skill was missed the least amount of time (30% for both questions). The second skill is the definition of $K$ in terms of mole fractions and pressure. Three questions require the student to demonstrate this skill. Comparing the performance of two of the questions suggests that the problem is that the students do not remember the pressure dependence in the definition of $K$. The pressure dependence is not used in obtaining the answer with one question (31% miss rate) but is used in another question (69% miss rate). It appears that the majority of all wrong answers for this latter question occur from this particular mistake relating to pressure dependence.

Based on the above analysis, it appears that the students grasp the concept of $\Delta G^o = -RT\ln K$, but do not grasp the concept of $K = \left( \prod_i y_i^{v_i} \right) P^{v_i}$. In an effort to reinforce this concept, a recommendation was given to three (one sophomore and two junior) courses to focus on calculating equilibrium concentrations from $K$ at pressures other than 1 bar.

Competency 3.7.1.2

This competency states that a student will be able to solve first-law problems for closed systems. The L3 exam has a total of six questions that cover this competency. The miss rates ranged from 17-56%. There are basically four skills involved in this competency. The first skill is recalling that $dU = \delta Q + \delta W$. The second skill is relating $dU$ to measurable variables. To ensure the math does not become difficult, all questions concern either ideal gasses or liquids so $dU = C_v dT$. The third skill needed is calculating the work in terms of measurable variables. For problems involving gasses, this is restricted to PV work and is $\delta W = -P_{ext} dV$. The forth skill needed is an understanding of reversibility and that for reversible processes, $P_{ext} = P = RT/V$ (for the ideal gas problems).

One question concerns the third skill. The miss rate on this problem is 26%. As such, it appears that students understand $\delta W = -P_{ext} dV$. One question, with a miss rate of 17%, concerns only the first two skills, suggesting the students understand the first law and the relationship between $dU$ to $C_v$. One qualitative question, with a miss rate of 41%, asks the direction of the temperature change for an adiabatic/reversible process. The majority of the students missing the question answered that the temperature doesn’t change. From this data, it appears student may confuse the term adiabatic with isothermal. Two questions with miss rates of 46% and 55% require the
student to calculate $\Delta U$ from $C_v \Delta T$ to determine either $T_2$ or $W$ given the other variables. The popular incorrect answers for these problems come from assigning the incorrect sign to either $Q$ or $W$ or both. It therefore appears that students do not understand the sign convention governing the directionality of the flow of energy. The most-missed question (56% miss rate) involves the fourth skill. Students must calculate the reversible work. The incorrect answer most often cited is arrived at by calculating $\delta W = -P_{ext}dV$ rather than $\delta W = -(RT/V)dV$.

In summary, it seems students have three problems with the first law competency. First, they confuse adiabatic with isothermal. Second, they do not understand the correct sign convention governing the directionality of energy flow. Third, they do not understand the implications of reversibility. This information is being provided to appropriate courses to help strengthen these concepts.

**Conclusions**

As noted, students do very well in passing the L3 exam. The designation of L3 competencies has helped faculty and students focus on foundational concepts. The L3 exam has provided an assessment tool for Level-3 competencies and has been a means of demonstrating student mastery of these concepts. During the analysis of the missed competencies, we have found useful insights into student thought processes and potential misunderstandings which are leading to clearer and better classroom instruction. As we have investigated student performance on competencies, three of the competencies (10.1.1, 3.7.3, and 3.7.1.2) have been consistently ranked near the highest in terms of miss rates. Initial recommendations focus on increased instruction in the competencies across several courses as well as changes in the information available to students during the L3 Exam. Follow up with the recommendations will determine whether the recommendations are sufficient to reduce the miss rates or whether further recommendations, such as adjustments in teaching style (e.g. hands-on), need to be employed. We hope and expect the L3 Exam to continue to be a useful means of assessing student performance and of continuing the improvement of teaching and learning.

**References**