Meeting ABET EC 2000 Criterion 3 Outcomes with a Laboratory Course

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1 Introduction

Colorado School of Mines (CSM) is a public research university devoted to engineering and applied science that has distinguished itself by developing high-quality graduates and scholarship. The U.S. News and World Report Inc. rated CSM 26th in the Top National Public Universities and 50th in the Best Undergraduate Engineering Programs with Ph.D. Programs in 2001[1]. The school's mission as written in the Colorado statutes focuses on "energy, minerals, and materials science and engineering and associated engineering and science fields." The sequence of multidisciplinary laboratory courses described herein lies within the engineering focus and is taught within the Engineering Division.

The Engineering Division is the largest program at CSM with approximately 850 undergraduate majors and 70 graduate students. This population represents a shift from the CSM's historical earth science and engineering focus. The CSM undergraduate program has been continuously accredited by the Accreditation Board for Engineering and Technology, Inc. (ABET) since program inception in 1983 as a non-traditional, interdisciplinary, Bachelor of Science Degree in Engineering with specialties in civil, electrical, environmental, and mechanical engineering. The Engineering Division also delivers graduate degree programs (M. S., M. E. and Ph. D) and research in engineering systems. The Gourman Report ranks the CSM Engineering Division fifth among general engineering programs[2].

This paper describes the results of using a laboratory course sequence as a centerpiece during an ABET evaluation during the 2000-2001 Evaluation Year under the new EC 2000 criteria at CSM. The EC 2000 criteria are described on the ABET website.[3] The CSM Self Study Report was completed at the beginning of the Fall Semester 2000 and the ABET team visited campus during the middle of the Fall Semester 2000. The preliminary results from the team exit interview were encouraging, so we would like to share information on how to design and present laboratory courses that can become centerpieces for ABET evaluations at other universities.

The Multidisciplinary Engineering Laboratory (MEL) sequence was initiated in 1997 by replacing three traditional, closed, theory-verification laboratory courses in electrical circuits, fluid mechanics, and stress analysis[4]. MEL's educational objectives are implemented with a sequence of experiments that transition from closed to open-ended and that increasingly integrate multiple subjects. The goals of MEL are to prepare graduates who can integrate multiple disciplines, extend their knowledge to new topics over their professional lifetimes, be team and project leaders, and implement instrumentation in engineering projects and products. The courses (MEL I, MEL II, and MEL III) are taught in sequence in the sophomore, junior and senior years to facilitate implementing a complex set of educational objectives.

To encourage the development of open-ended problem solving skills, the MEL courses avoid the step-by-step procedures presented in traditional laboratory courses. In these types of courses, students can just go through the motions to get the information necessary to “fill in the blanks” in a laboratory report and not really understand the material. In MEL, students are presented with a simulated industrial problem, provided with a set of reference information and hardware, and expected to design their own experimental procedure. The students review the reference information and the objectives in the laboratory, plan a procedure, and prepare a simple model that is submitted before class. Once in class, they assemble the apparatus, perform the experiment, modify their procedure, and report their results.

2 Correlating CSM Goals and Objectives with ABET Criterion 3 Outcomes

The title of our paper focuses on Criterion 3, “Program Outcomes and Assessment.” Criterion 3 is one of eight criteria in part II. “Basic Level Accreditation Criteria” in the ABET EC 2000 criteria. The ABET EC2000 criteria requires that universities and programs have a process for continuous improvement. The process flow shows that Criterion 3 is based on objectives developed by the institution and program in Criterion 2 which requires "(a) that an engineering program have detailed published objectives that are consistent with the institution’s mission, (b) a process to determine and evaluate objectives, (c) a curriculum and process that ensures the achievement of the objectives, and (d) a system of ongoing evaluation[3]." So, prior to describing the correlation between what we teach in MEL and the Criterion 3 outcomes, shown in Table 1, we will set the stage by summarizing the institutional and program objectives.

Table 1. ABET EC 2000 Criterion 3 Outcomes [3] (paraphrased).

	Graduates must be able to (have):
a	apply knowledge of math, science and engineering
b(i)	design and conduct experiments
b(ii)	analyze and interpret data
c	design a system, component or process
d	function on multidisciplinary teams
e	identify, formulate and solve eng. problems
f	understand ethical and professional responsibility
g	communicate effectively
h	understand the impact of engineering solutions in a global and societal context
i	recognize need for and engage in life-long learning
j	(a knowledge of contemporary issues)
k	use modern tools for engineering practice

Two terms “goals” and “objectives” require a brief explanation. At CSM, goals are desired educational attributes that characterize graduates. Our objectives are clearly identifiable and measurable elements of student achievement. We believe our use of the term “objective” is very close to the use of the term “outcome” by ABET[5].

Table 2 shows the correlation between the institutional goals “the profile of the CSM graduate,” and the ABET outcomes.

Table 2. Correlation Between CSM Goals and the ABET EC 2000 Criterion 3 outcomes[5].

Colorado School of Mines Graduate Profile (1994)	ABET EC 2000 Criterion 3 Outcomes*
All CSM graduates must have **depth in an area of specialization**, enhanced by **hands-on experiential learning**, and **breadth in allied fields**. They must have the **knowledge and skills** to be able to **recognize, define and solve problems by applying sound scientific and engineering principles**. These attributes uniquely distinguish our graduates to better function in increasingly competitive and diverse technical professional environments.	a, b, c, e, k
Graduates must have the **skills to communicate information, concepts and ideas** effectively **orally, in writing, and graphically**. They must be **skilled in the retrieval, interpretation and development of technical information** by various means, including the use of **computer-aided techniques.**	g, k
Graduates should have the **flexibility to adjust to the ever-changing professional environment** and **appreciate diverse approaches to understanding and solving society's problems**. They should have the **creativity, resourcefulness, receptivity and breadth of interests to think critically about a wide range of cross-disciplinary issues**. They should be prepared to assume **leadership** roles and possess the **skills and attitudes which promote teamwork and cooperation and to continue their own growth through life-long learning**.	c, d, e, h, i, j
Graduates should be capable of working effectively in an **international environment**, and be able to succeed in an increasingly **interdependent world where borders between cultures and economies are becoming less distinct**. They should **appreciate the traditions and languages of other cultures, and value diversity in their own society**.	d, h
Graduates should **exhibit ethical behavior and integrity**. They should also **demonstrate perseverance and have pride in accomplishment**. They should assume a **responsibility to enhance their professions through service and leadership** and should be **responsible citizens who serve society, particularly through stewardship of the environment**.	f

* refer to Table 1 for description of ABET EC 2000 Outcomes

Each program at CSM has separate goals closely related to the institutional goals. Table 3 shows the Engineering Division Goals and their correlation with the ABET outcomes.

Table 3. Correlation Between Engineering Program Goals and ABET EC 2000 Criterion 3 Outcomes[5].

Engineering Program Goals	ABET EC 2000 Criterion 3 Outcomes*
Graduates will understand the design and analysis of engineering **systems** and the **interdisciplinary nature** of engineering.	b, c, d
Graduates will have an appreciation for **engineering practice** as it relates to the earth, energy, materials and the environment.	e, h, k
Graduates will have the **engineering expertise** and **lifelong learning** skills to meet the present and future needs of society.	e, f, i
Graduates will be able to incorporate non-technical constraints and opportunities (i.e. aesthetic, **social, ethical,** etc.) in their e**ngineering practice.**	f, h, j
Graduates will be well prepared to assume entry-level positions in industry or to enter appropriate graduate programs.	a, b, c, d, g, i

*refer to Table 1 for description of ABET EC 2000 Outcomes

With the background of the CSM and program goals, we will look at the relationship between MEL and other courses in the Engineering Division Program in meeting the ABET outcomes. Not every course in the program needs to meet all of the outcomes, since graduates will meet all outcomes only after taking a group of required courses. Furthermore, universities can provide programs that intend to reach outcomes in addition to those specified by EC 2000 Criterion 3. For our ABET evaluation, the CSM Engineering Division selected the group of core courses, shown in Table 4, to meet the required outcomes. We supplied additional tables showing correlations for other courses in each of our four areas of specialty[5].

Table 4. Meeting the EC 2000 Criterion 3 Outcomes with a Group of Courses[5].

Keyword Extracts from EC 2000 Criterion 3 Outcomes		Core Courses in Engineering									
		EGGN 233**	EGGN 250	EGGN 315	EGGN 320	EGGN 350	EGGN 351	EGGN 371	DGGN 381	EGGN 491	EGGN 492
a	apply knowledge of math, science and engineering	P*	P	P	P	P	P	P	P		
b(i)	design and conduct experiments	P	P			P			S	P	P
b(ii)	analyze and interpret data		P			P	S		S	P	P
c	design a system, component or process	S	P			P	S			P	P
d	function on multidisciplinary teams		P			P			S	P	P
e	identify, formulate and solve eng. problems	S	P	P	P	P	P	P		P	P
f	understand ethical and professional responsibility		S			S				P	P
g	communicate effectively		P			P				P	P
h	understand engineering solutions in global and societal context									S	S
i	recognize need for and engage in life-long learning	S	P			P	S			S	S
j	knowledge of contemporary issues		P			P				S	S
k	use modern tools for engineering practice	P	P	P		P	S	S	S	P	P

*P:= primary emphasis, S = secondary emphasis, Blank = negligible emphasis

** EGGN 233 = Field Session, 250 = MEL I, 315 = Dynamics, 320 = Strength of Materials, 350 = MEL II, 351 = Fluid Mechanics, 371 = Thermodynamics, 381 = Electrical Circuits, 491 = Capstone Design I, 492 = Capstone Design II.

With this background of institutional and program goals and their correlation to the ABET outcomes, we will begin a detailed assessment of the contribution of our MEL course sequence to the ABET evaluation. Obviously, a laboratory course should match criterion 3 a, b(i), and b(ii), but after careful analysis we found that the MEL objectives, shown in Table 5, matched nearly all of the ABET outcomes with the exceptions of 3f and 3h (and if necessary, the course could be modified to incorporate these objectives in the future). Note that most traditional engineering science lecture courses meet criteria a: apply knowledge of math, science and engineering; criteria e: identify, formulate and solve engineering problems; and criteria k: use modern tools for engineering practice. Only MEL and capstone design meet those, as well as, other criteria.

Interestingly, we did not consider the EC 2000 outcomes when we developed the educational objectives for MEL. MEL objectives were based on the CSM graduate profile, the Engineering

Program goals, and the pedagogy linking subject matter competency with thinking maturity and life-long learning[4]. The result that the MEL objectives matched well with the EC 2000 outcomes enhanced our confidence in the process and pedagogy used to formulate the objectives for MEL, and increased our respect for those who developed the EC 2000 Criterion 3 outcomes.

Table 5. Relationship Between MEL Educational Objectives and ABET EC 2000 Outcomes.

MEL Educational Objectives	Type of Correlation with ABET Outcomes*	
	Primary	Secondary
Enhance student's thinking skills.	e,i	
Encourage students to integrate knowledge from several courses.	a	
Emulate industrial practice by using a systems and applications context.	k	j
Build subject matter competency in fundamental engineering topics.	a	
Actively learn the skills of efficient and accurate experimenters.	b(i),b(ii),c,d,k	a
Improve student retention of laboratory/experimental skills and hardware.	b(i),b(ii),c,d,k	a
Build life-long learning skills.	i	
Experience a variety of learning styles.	i	
Enhance group and teamwork skills.	d	
Enhance communications skills.	g	f,k

* refer to Table 1 for description of ABET EC 2000 Outcomes

3 ABET Evaluation of Laboratories at Other Universities

We searched the literature to find other examples of the contribution of laboratory courses in meeting the ABET outcomes. The Department of Chemical Engineering at Carnegie Mellon University (CMU) applied Problem Based Learning methods to modify a traditional theory verification laboratory course[6]. At CMU, problems supplied by local industries are given to a team of three to four students that solves two problems per semester. Project teams present oral and written reports midway through and at the end of the seven weeks. Students alter equipment designed for mobility and flexibility to meet the needs of their problem. The resulting outcomes closely match those required by ABET: open-ended problem solving, experimental design, effective teamwork, information gathering, and oral and written communications; however there was no report of the program or course being evaluated by ABET under the EC2000 criteria.

In another example, Hyman described an experience with ABET accreditation for the Bioengineering Laboratory courses at Texas A&M[7]. The laboratory experience at Texas A&M, which was accredited in 1977, and was hopefully being reaccredited in 1981 as the article was written, included laboratories in several other disciplines. The evaluation was conducted with historical ABET criteria, which required laboratory experiences in both basic sciences and engineering courses, but no experimental design, and no continuous improvement process.

Nevertheless, Hyman suggested that laboratories should reflect the objectives of the program and ABET should not require all universities to offer the same laboratory experiences. The new accreditation process was designed to permit this flexibility.

Laboratories in the Department of Civil, Environmental, and Chemical Engineering at Youngstown State University do not match all of the EC2000 criteria, so they propose to cooperate with service departments in Chemistry and Physics to provide the EC 2000 b(i) and b(ii) outcomes in designing and conducting experiments and analyzing data as well as on other outcomes[8].

4 Implementing Objectives in MEL to Meet EC 2000 Criterion 3 Outcomes

Based on the previous explanation of the CSM and Engineering Division goals and objectives along with their correlation with the ABET outcomes, we will now explain how the MEL course sequence meets each of the outcomes (with the two exceptions).

4.1 ABET outcome a: apply knowledge of math, science and engineering

We require students to apply math, science and engineering in several ways in every MEL experiment. We require students to complete a pre-experiment report before coming to class that has two parts. The first part is a model and the second is a planned procedure. This activity helps students to understand the material, predict results from their forthcoming experiment, recognize experimental errors, connect multiple subjects, and develop questions to ask the instructor.

For example, in one of the experiments in the sophomore course, MEL I, we ask students to use a thermistor equation, $\frac{1}{T} = a + b\ln(R) + c(\ln R)^3$ and the equation for a voltage divider circuit, V_{out} = (Vs + R_t)/ (R_1 + R_t) to predict voltage drops at freezing, room temperature, and boiling for a given thermistor. This requires them to solve for R in terms of the constants and T, so they have to review mathematical methods like Newton’s method or a graphical method, choose one, and apply it. Next we ask them to assume a different thermistor with unknown constants for which they measure three voltages and three different temperatures and then solve a system of equations using matrices, Cramer’s rule, or substitution algebra. Students will compare these numbers with data gathered during the experiment.

Another application of math, science and engineering is the requirement to connect concepts from several subjects in one experiment. In an example from the junior course, MEL II, a pre-experiment report question asks students to determine the necessary amplification for a signal from a pressure transducer connected to a hydraulic fluid-power circuit on a materials-testing machine. The pressure-transducer signal will be used to calculate the load applied to a steel specimen. The students must connect fluid mechanics, instrumentation, and experimental stress analysis concepts to solve the problem of determining the appropriate level of amplification. They will set this level in software running on their data acquisition system (DAS) when they begin the experiment.

For brevity, these examples summarized simple applications of math, science, and engineering. More detail on all of the MEL experiments, pre-experiment reports, results reports, and reference material is available in the laboratory manuals[9,10,11] and on the course website by following the links from the CSM website[12] to the Engineering Division and to the MEL course sequence.

4.2 ABET outcome b(i): design and conduct experiments

In each MEL experiment, students are presented with a simulated industrial problem and asked to design an experimental procedure to gather data for analyzing and solving the problem. For example, a MEL II experiment states, “A company needs to measure flow rate to control processes. You have been asked to evaluate several transducers and describe them fully in an engineering report so the company will have a reference for selecting particular types for particular applications[10].”

We are faced with at least the following constraints in asking students to completely design a complex experiment:

- Students are inexperienced.
- The time available for them to complete and evaluate a design is very limited.
- We need to teach similar integration of subjects uniformly to a large number of students.
- There isn’t enough time available to purchase new hardware, and we do not have the resources to maintain a large inventory of diverse hardware.

Therefore we devised a sequential approach where experimental design becomes more complex and open-ended as students become more proficient through the sequence of courses. Then, we provide the hardware for each experiment and the entire class performs the same experiment. To maintain a limited hardware inventory, we ask students to design procedures but not to select hardware. To give students some experience at hardware and instrument selection, we ask them to prepare a design that improves on the instrumentation and hardware available. For example, a MEL-III experiment states: “Evaluate the instrumentation system and recommend improvement[11].” So far, we have not introduced statistical processes for designing experiments to improve product quality, but that could be added to MEL in the future.

4.3 ABET outcome b(ii): analyze and interpret data

Every MEL experiment requires students to analyze and interpret data. For example, in MEL I, students are required to perform actions like the following:

- Compare model and experimental results and explain differences.
- Compare actual tolerances of components with manufacturer’s specifications.
- Determine the resolution error.
- Calculate period and frequency of the signal waveform
- Determine the sampling frequency using the Nyquist theorem.
- Use the thermal and strain measurements to calculate the thermal expansion coefficient of the specimen.
- Calculate linearity, hysteresis, repeatability, and zero offset errors.

- Calculate transducer sensitivity.
- Present a time-domain graph.
- Present a power spectrum graph.
- Calculate the potential, kinetic and total energy values and graph the respective waveforms. Discuss the relationship between kinetic and potential energy.
- Write 2000 point of 1000 S/s Harmonic oscillation data from the accelerometer to a spreadsheet file. Calculate acceleration, velocity, and displacement for each point. Graph the waveforms. Predict the values of the signals at t = 0 and compare with the results.
- Calculate the maximum, minimum, average, and standard deviation of the peak shock values. Use the measurements to compare the different types of packing material.
- Compare the three filters by calculating and graphing frequency vs. predicted transmittance and measured transmittance. Determine the number of frequency values necessary to completely evaluate the performance of each filter.
- Develop a Bode Plot of the microphone data.
- Calculate the resolution error along the waveform. Differentiate and integrate the resolution error. Discuss the effects of differentiation and integration on the signal.
- Smooth the calculated velocity data from the experiment to create a +/- 25% error from the predicted values. Determine the number of points required to smooth to this level. Determine the actual time resolution of the data.
- Plot angular velocity vs. motor voltage. Determine rpm by averaging a number of cycles. Include average velocities at 10 or more voltages.

4.4 ABET outcome c: design a system, component or process

As discussed earlier, the MEL experiments are all multidisciplinary systems. MEL does not verify theories within a discipline. To encourage the development of open-ended problem solving skills, the MEL courses avoid the step-by-step procedures presented in traditional laboratory courses. In a traditional experiment, students are given a series of steps to follow to verify a theory. In MEL, students are presented with a simulated industrial problem, provided with a set of reference information and hardware, and expected to design their own experimental procedure. We believe evaluation is an important step, so students learn the shortcomings of their design. Therefore, once in class, they assemble the apparatus, perform the experiment, modify their procedure, and report their results along with the final procedure.

4.5 ABET outcome d: function on multidisciplinary teams

Students from all of the specialties of the engineering division take MEL I and II and a subset take MEL III. In addition, students from other departments like petroleum engineering take MEL I and II; therefore most of our teams are multidisciplinary. Students have to function efficiently on the teams because we limit the team size to three students, and the team must complete a large amount of work during the three-hours per week available in the laboratory.

4.6 ABET outcome e: identify, formulate and solve engineering problems

Each of the MEL experiments is a simulated industrial problem. Some examples from MEL III are:

- Develop a hardware and software system to automatically control a fatigue test at the fastest load cycle possible with the given equipment.
- Analyze the data collected from several refrigeration cycles and diagnose the problem with the refrigeration system.
- Analyze the data collected from several refrigeration cycles and redesign the refrigeration system to reduce energy consumption.
- Collect data from riding a mountain bike over a set course. Develop a model of the bicycle suspension using Working Model software. Compare the data to the model and evaluate the effectiveness of a the suspension. Redesign the suspension to improve effectiveness.

4.7 ABET outcome g: understand ethical and professional responsibility

We tie ethical and professional responsibility to written communication activities. For example, students calibrate a CSM-built pressure transducer and write a specification sheet based on the calibration that would be used in marketing the transducer for a simulated company. They study specification sheets from other manufacturers in the process. Through discussion and grading feedback the ethical responsibility of correctly reporting the calibration sensitivity and errors becomes clear. In this experiment and others, we emphasize proper reporting of data in graphs without exaggerating axes scales to hide or emphasize conclusions.

Furthermore, students use a lot of information from the web and other sources in their reports. Through feedback and instruction, proper referencing is emphasized. In addition, we have strict academic integrity standards to prevent using any non-original data or reports.

4.8 ABET outcome h: communicate effectively

MEL is part of the writing across the curriculum program at CSM and integrates with written communication instruction and practice in freshman-level Design I, sophomore-level Design II and senior-level Capstone Design I and II courses. In MEL I, students write in a laboratory notebook, write short answers on the pre-experiment and results reports, correctly write equations and define symbols and variables, and correctly format graphs for data presentation. They repeat these activities in MEL II, but instead of short answers to questions on the report forms, they write memo reports and short engineering reports. In MEL III they extend written communications to full engineering reports. We use Beer and McMurrey[13] throughout the writing across the curriculum sequence as a standard writing reference.

4.9 ABET outcome i: recognize need for and engage in life-long learning

The discussion of this issue will be longer than that on the previous ABET outcomes since the necessary pedagogy and the characteristics of a life-long learner are not widely published or agreed upon across the engineering-education community. Furthermore, this is a key objective in MEL and many of our instructional activities stem from it. Therefore it is necessary to explain our approach.

Confident students with a strong background in engineering fundamentals and mature thinking exhibit characteristics of independent life-long learners. We use the Perry Model[14] to define and measure thinking maturity, and we have compared it to other work like Bloom's Taxonomy[15]. Based on an assessment of the two, we would expect higher-level thinkers to possess the following abilities:

- Reduce complex systems to their component parts.
- Assemble components into a structure not clearly there before.
- Accept ambiguity and identify and develop alternative solutions to a problem.
- Make judgments using criteria and evidence.
- Make commitments.

We believe higher-level thinkers are more apt to become life-long independent learners. Many students are dependent learners at the Perry Model Level of Dualism where they view teachers as absolute authorities[14]. Our goal is to help them mature beyond the level of Multiplicity to the level of Contextual Relativism, where learners accept their self as a legitimate source of knowledge. At this level, authorities help, but the student is the active maker of meaning. Students take responsibility for learning, and they use evidence to evaluate alternatives and make judgments about the best solution to a problem. This sets the stage for students to mature to higher levels like Commitment within Relativism where students are committed to learn and committed to struggle with problems whose solutions are not clearly evident. Commitment, self reliance, identification of alternatives, and use of evidence are characteristics of life-long learners that are congruent with models of the thinking maturity process.

One way that we encourage higher-level thinking is to ask students to develop their own experimental procedures as discussed previously. By following the process described previously, they learn how to develop procedures on their own, an important characteristic of life-long learners. They learn to identify what information is necessary, gather the information from reference sources, and use it to develop a procedure. For example, we don't instruct students in the operation of some instruments. They must locate operating information and use it to correctly use particular instruments. Other important ingredients are integrating material from multiple subjects and building more complex and sophisticated systems through a sequence of courses.

4.10 ABET outcome k: use modern tools for engineering practice

Every experiment in MEL uses modern tools found in engineering practice for example:

- Computer data acquisition systems
- Graphical user interfaces
- Modern graphical programming tools
- Transducers – strain gage, thermistor, accelerometer, linear potentiometer, pressure, flow meter, proximity transducer, optical encoder, rotary potentiometer
- Actuators – proportional hydraulic fluid power valve, mass flow controller
- Instrumentation – multimeter, function generator, oscilloscope, bridge shunt calibrator

5 Evaluation/Project Results

MEL was introduced to the curriculum gradually and carefully by first offering a pilot course of MEL I, evaluating it and making modifications before obtaining approval to replace a traditional laboratory course. A similar process was followed later for MEL II, and finally MEL III. We taught a pilot course during the same semester as a traditional course that was ultimately replaced by MEL.

The ABET EC 2000 requires a process of evaluating performance. We conducted several assessments during the development of the MEL sequence. King et al[16] provides full assessment reports. The following sources were used for assessment data:

- Independent Evaluator Classroom Observation
- Focus Groups Led by Independent Evaluators
- Survey Instrument
- CSM Student Evaluation Forms
- Alumni Survey
- Exam Questions

5.1 Independent Evaluator Group Assessment of MEL I

After developing and evaluating MEL I, the independent evaluators concluded that MEL I definitely met its goals; it caused more and deeper learning, with obvious integration of topics and student excitement about the experience. However, they were concerned that MEL may be at the extreme end of what students can handle.

During development, students completed a written survey[16]. Table 6 summarizes the results of the question on engineering knowledge and skills where 4 = strongly agree and 0 = strongly disagree.

Table 6. Gains in Engineering Knowledge and Skills

Components	**Mean Score**	
	EGGN 383	**MEL**
a. This lab requires me to apply knowledge of mathematics, science or engineering.	2.82	3.61
b. I feel that I can apply what I've learned in this lab to real world problems.	2.27	3.17
c. My lab class really requires me to think about what I am doing rather than just plugging numbers into formulas.	2.73	3.70
d. This lab teaches me to design and conduct experiments.	2.55	3.39
e. This lab teaches me to analyze and interpret data.	2.73	3.43
f. My lab class is preparing me for higher level engineering courses.	2.18	3.22
g. This lab provides me with the ability to use the techniques, skills, and modern engineering tools necessary for engineering practice.	2.55	3.13
h. I feel confident that I could design an experiment to calibrate a new laboratory or field apparatus or sensor that my future employer might purchase.	1.55	2.78
i. This lab teaches me to solve engineering problems on my own.	2.45	3.17

Our assessment continued during the spring semester, 1998, with MELII. The independent evaluator report[16] concluded:

1. Students refer to traditional labs as “plug and chug” and to MEL as “open-ended”. It was clear that MEL students sometimes wrestled with the fact that open-endedness requires more time and effort on their part.

2. MEL students mentioned that because the lab procedure was not specific that they needed to communicate with their lab partners. Students in traditional labs also communicate with each other, but on a more ad hoc basis.

3. Written communication skills stressed in some traditional labs, but there is not as much opportunity to practice verbal communication skills in traditional labs as there is in MEL labs.

4. MEL students said explicitly that teamwork was more important in MEL than in other labs because one needed to rely on other students to determine the lab procedure.

5. During observation of MEL and traditional labs, MEL students were more consistently engaged in the particular task at hand and with each other.

The students in the course evaluate all courses at the Colorado School of Mines. The final report to FIPSE[16] contains details on the analysis of student evaluation scores of all MEL courses from

Spring Semester 1977 through Summer Semester 1999. The conclusions from the data analysis were:

MEL III scores were the highest, followed by MELII, and MEL I. In general, students were satisfied with the course, but they believed MEL was too much work for the amount of credit. They also requested improvement in the Laboratory Manuals.

Independent evaluators conducted a telephone survey of CSM Alumni who completed one or more of the MEL courses[16]. The following summarizes the responses.

To what extent did MEL mirror what you do in your job?

In general, most respondents used the teamwork skills, open-ended problem solving skills, and knowledge of working with multidisciplinary systems. A few used the technologies taught in MEL.

What worked in MEL, what didn't?

Initially the hardware was not reliable and the course was disorganized, but it improved every semester. After a few semesters, the hardware and experiments for implementing the multidisciplinary concepts seemed to work well. But some students may not have been mature enough to thoroughly comprehend the concepts in MEL I. The laboratory computer systems did not always work as well as they should.

What did you see as the strengths and shortcomings of your MEL Lab courses?

The course was more oriented to real-world applications than traditional laboratory courses. However, non-EG majors were not comfortable with the course, and there seemed to be too much work for the number of credit hours.

6 Conclusion

The CSM Multidisciplinary Engineering Laboratory (MEL) sequence replaced three traditional, closed, theory-verification laboratory courses in electrical circuits, fluid mechanics, and stress analysis with more open-ended experiments that integrate multiple disciplines and more closely mimic industry practice. MEL became a centerpiece in the ABET evaluation underway during this evaluation year. To encourage the development of open-ended problem solving skills, the MEL courses avoid the step-by-step procedures presented in traditional laboratory courses. The courses are taught in sequence (MEL I, MEL II, and MEL III) in the sophomore, junior and senior years to facilitate implementing a complex set of educational objectives. Students who graduate after completing the MEL sequence have qualifications that match the ABET required abilities to:

- apply knowledge of math, science and engineering
- design and conduct experiments
- analyze and interpret data
- design a system, component or process

- function on multidisciplinary teams
- identify, formulate and solve eng. problems
- understand ethical and professional responsibility
- communicate effectively
- recognize need for and engage in life-long learning
- use modern tools for engineering practice

MEL has impacted CSM in areas other than the ABET accreditation. Based on the results of implementation, evaluation, and improvement, MEL has become a major focus of the undergraduate program in engineering at CSM. In addition, it became the focus of a recent Program of Excellence award from the Colorado Commission of Higher Education and an award from the American Council on Education for enhancing educational quality while controlling cost. Furthermore, CSM has allocated a sizeable piece of a new building, the Center for Technology and Learning Media, to the MEL program, and we presented proposal to the State of Colorado to build an addition to the current Engineering Division building (George R. Brown Hall) based on MEL pedagogy and accomplishment.

5 Acknowledgments

Financial support for course development was provided by FIPSE (Fund for the Improvement of Post Secondary Education, U.S. Department of Education) Grant P116B51710. CSM and the Parsons Foundation provided funds for the MEL I experimental apparatus and laboratory modification. NSF ILI Program Grant DUE-9850556, CSM, Chevron, and Kennecott provided funding for MEL II and III experimental apparatus and laboratory modifications necessary to develop the multidisciplinary sequence. NSF Grant DUE-9653726 provided conference travel funds.

Dr. Nigel Middleton wrote the original FIPSE proposal with Dr. Parker, Gosink, and Glazer. Dr. Terry Parker developed the initial experiments for MEL I and II. Dr. Tom Grover developed much of the experimental equipment for the MEL sequence. Drs Gosink, Pavelich, Olds, Pang, and Streveler conducted assessment activities.

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