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A Course in Problem Solving with Experimental Design

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Abstract

To address needs for accreditation and our university's requirements for graduation, we have implemented a sophomore-level course on problem solving and experimental design. This course reinforces problem-solving strategies from material and energy balances and requires students to establish their own experiment designs to explore chemical and physical phenomena related to junior-level thermodynamics and transport courses. Concepts in statistics and numerical methods, technical writing, engineering ethics, and laboratory and industrial safety are all introduced in the scope of this course.

This course serves as the first in our curriculum where students are responsible for the creation of laboratory procedures, in contrast to their typical chemistry labs where experimental methods are provided. Given a brief (1/2-1 page) prompt explaining the principle of interest and a list of available laboratory equipment, students are required to explicitly outline the objective, hypothesis, and methods of their experiment, followed by statistical analysis of their data and consideration of relevant theory. The course is structured in such a way that students must determine which statistical techniques are appropriate for processing their experimental data. The course is also designed to meet the Writing Intensive requirements of our university, through a combination of individual lab reports, reflections on their ability to write in a technical context, and brief essays on engineering ethics and laboratory safety.

Specific course logistics, including the sequence of activities, learning objectives, and connections to student outcomes in junior- and senior-level courses, are considered here. Direct assessment of student performance against specific learning objectives from the past three years is shown here as an example of how the course is continuously improved.

Motivation and Introduction

A course in experimental design for chemical engineers has been developed by faculty at the University of Maryland Baltimore County (UMBC) to address the needs of our students and administration. The chemical engineering curriculum is often under scrutiny from administration to reduce the number of credits and number of prerequisite service courses taught by other departments. Our students also express, through feedback mechanisms such as exit surveys, a desire to be exposed to application of early prerequisite material, finding courses like technical writing to be too broad and introductory mathematics courses to be too focused on mechanics and not enough on applications. In response to the needs of our university, there is now a four-credit course in chemical engineering problem solving and experimental design, a course structured to introduce students to ideas in statistics, technical writing, and engineering ethics in ways to reduce the need for separate courses for each. The course also helps provide context to these concepts in ways that were not being done in traditional full courses.

The rest of this paper is organized as follows. First, a general overview of our institution and the position of this course in the chemical engineering curriculum is explained. Next the course content and learning objectives are established, followed by the course sequence of events and assessments. Finally, an example of how these assessments are used to continuously improve the course is given.

Institution and Curriculum

UMBC is a medium-sized, Northeastern, public institution whose student body is comprised of approximately 75% full time and 25% part time students. The overall student population is 53% male and 47% female and is diverse with about 40% of students representing minority populations. In chemical engineering, the student population is 63% male and 37% female with 46% minorities.

The experimental design course is a required course typically taken in the spring of the sophomore year (as the only required chemical engineering course) or in the fall of the junior year (concurrently with thermodynamics and fluid mechanics). Its prerequisite is solely material and energy balances; most students have completed a three-semester calculus sequence and are currently taking differential equations, but there is no formal mathematics requirement for this course. Its position in the sequence of required classes was chosen to introduce concepts related to thermodynamics and transport prior to the traditional lecture-based courses. Experimental design is a four credit course that meets 150 minutes a week for problem-solving sessions and an additional 110 minutes per week in either a computer lab or experimental lab. It is a strict pre-requisite for the senior-level laboratory courses, and, because of its introduction of computer programming techniques, process control.

It is important to note that our curriculum has no specifically required courses in linear algebra, statistics, engineering ethics, or technical writing. Instead, concepts from these courses are embedded in multiple courses in our curriculum. Experimental design is the first to introduce many of these concepts, with later courses in the curriculum continuing to build on these.

As an early course in our chemical engineering curriculum, experimental design serves as the first place where certain ABET criteria are documented; all of these criteria are assessed formally in the final year of the curriculum as the formal student outcomes a-k. [(1)] In experimental design, a preliminary assessment is made for outcomes b (ability to design and conduct experiments and analyze and interpret data), d (ability to function on teams), e (ability to identify, formulate, and solve problems), f (understanding of professional ethics), g (ability to communicate in writing), and k (ability to use techniques, skills, and modern tools). Evaluation of this preliminary assessment is used to inform the structure of future iterations of this course.

Course Content

The major learning objectives of the course can be summarized as follows. After taking this course, our students are expected to be able to

- Apply problem solving skills associated with chemical engineering
- Use computer tools including Excel and MATLAB to analyze data and construct models
- Apply structural elements, including input/output, loops, conditionals, and array manipulation, to computer programs
- Apply statistical concepts associated with experimentation, including hypothesis testing, statistical significance, and calculation of measures of central tendency, variation, and error
- Develop basic skills associated with working in a group, practice leadership in a group setting, and apply tools to resolve (or avoid) conflict when working in a group
- Formulate responsible and ethical responses in personal and professional settings
- Apply the scientific and engineering methods, including hypothesis formulation and experimental design to test hypotheses, conduct experiments, collect and analyze data, and communicate results

A more detailed set of learning objectives, broken down under these seven main goals, is given in Appendix A.

The lecture component of the course is meant to give students exposure to a variety of ideas in inferential statistics, which students are later tasked to apply in the laboratory The specific statistical tools include the following.

- Confidence intervals on population mean, variance, and standard deviation
- Confidence intervals on regression parameters
- One-sample hypothesis tests on the mean (small and large number of trials), variance, and standard deviation
- Two-sample hypothesis tests on the mean (small and large number of trials, paired and unpaired data), variance, and standard deviation
- Hypothesis testing on correlation
- One-sample hypothesis tests on regression parameters
- One-Way, Two-Way, and N-Way Analysis of Variance (ANOVA)

The laboratory portion of the course provides opportunity to introduce ideas from engineering ethics and process safety while students design experiments. These topics include the following.

- Plagiarism and falsification of data
- Maintenance of a lab notebook
- Overview of basic ethical and philosophical theories
- Laboratory hygiene
- Inherently safer design

By introducing these concepts in a lecture setting and applying them in the lab, we hope to increase student ability to transfer course content, as well as motivate learning through practical examples. [2]

Course Structure

Our experimental design course is structured into two major parts, each lasting about seven weeks: the first half of the semester is devoted to statistical and numerical methods with the laboratory sessions devoted to computer work, and the second half focuses on experiments and laboratory safety with an introduction to engineering ethics and chemical process safety. This structure is in place to promote "transfer," or the ability to apply a skill in a new setting; [3] the second half of the course requires students to select the appropriate statistical analysis from the first half of the course for a given experiment.

The first half of the semester includes several low-stakes opportunities for developing skills before two higher-stakes exams toward the end, one on statistics and the other on computer programming. Class time is used to work practice problems with an additional follow-up problem due as homework for the next session.

A weekly outline of lecture and laboratory sessions for the first half of the course is presented in Table 1, below. The laboratory sessions are open-ended, guided by worksheets with gaps, as students work through MATLAB tutorials at their own pace. The instructor and teaching assistant circulate to address questions, and a deliverable is assigned, due at the start of the next laboratory session. When possible, lecture and lab are set up in sequence to inform one another, though there is some lag time leading to statistical analysis in Excel and MATLAB to provide students some time to review or learn basic MATLAB skills.

Table 1: Course Topics in First Half of Semester

Week	Lecture Topics	Computer Lab Work
1	Degree of freedom analysis; Linear algebra	Basic linear algebra functions
2	Descriptive statistics; confidence intervals	Scripts and functions
3	Single-sample hypothesis testing; Regression	Iterative methods (root finding)
4	General linear least squares; Interpolation	Statistical functions
5	Multiple-sample hypothesis testing	Numerical differential equations
6	Factorial design and ANOVA	MATLAB practical exam
7	Dimensional analysis and similitude	

The second half of the semester is much more group-oriented, with the focus on designing and conducting experiments. The online software CATME Team Maker [4] is employed with an awareness of student diversity and its contribution to the dynamics of individual groups. As our student body has a significant proportion of under-represented minorities of both genders, extra care is taken to ensure that individual students are not isolated within their groups.

The course continues to use the same meeting pattern as the first half, though most sessions are now devoted to group work. In some past semesters, lecture sessions were cancelled and replaced with office hours with the expectation that students would use this time to meet and work in their experimental design groups, but in other semesters, these lecture sessions were used to require group work while the instructor and teaching assistants circulate to address questions. Student feedback suggests that most students appreciate the increased structure and availability of instruction.

Once a week, lecture time is used to highlight process safety or ethics, and the rest is used for group conferences. The structure of the second half of the semester is roughly outlined in Table 2.

Table 2: Course Outline for Second Half of Semester

Week	Professionalism Topic	Lab Work
1	Technical communication	Simulation lab using MATLAB or Excel
2	Laboratory safety and hygiene [5]	Basic thermo lab (first law applications)
3	Introduction to inherently safer design	Basic fluids lab (mechanical energy balance)
4	Introduction to personal ethics	Intermediate thermo lab (Stirling engine)
5	Introduction to ethical theory and codes [6]	Intermediate fluids lab (terminal velocity)
6	Reading case studies	Mass transfer lab (brewing coffee; factorial design)
7	Connections to future courses	Mass transfer lab, continued

The most important feature of this half of the course is the structure of the laboratory assignments. The laboratory prompts are kept to about ½ page in length, introducing a problem or concept and tasking students to develop a hypothesis, design and conduct an experiment, analyze data, and discuss the implication of the results. A sample assignment is provided in Appendix B. Each design group meets with the course instructor once a week outside of class for a 15-minute meeting to discuss the previous and upcoming lab and address group dynamics concerns. [7]

A group lab report is due every week from design teams; these reports are graded quickly using an electronic form for feedback so that the instructor distills comments to the most important areas for improvement, rather than noting every detail that is out of place. This rubric is provided as Appendix C. Students are required to individually reflect on their group's performance in the lab and in their writing by explaining which parts of the instructor's feedback they considered most important and how they would improve for future reports. [8] A peer and self evaluation is due through CATME [9] after every other lab.

A final exam is conducted at the end of the term. This exam is designed to largely emphasize concepts from the professionalism and laboratory portions of the course.

The deliverables that are used to provided preliminary assessment of ABET outcomes are listed in Table 3. For formal accreditation purposes, these outcomes are considered again in the senior year in at least one course each; examples are given in the table.

Table 3: Deliverables for ABET Criteria Assessment

ABET criterion	Typical deliverable(s) in this course	Later course to assess this outcome
b (ability to design and conduct experiments and analyze and interpret data)	Exams; Lab Reports	Unit operations lab
d (ability to function on teams)	CATME Surveys; Group Contract; Meeting minutes	Capstone design
e (ability to identify, formulate, and solve problems)	Homework assignments; Lab reports	Capstone design
f (understanding of professional ethics)	Homework assignments	Capstone design
g (ability to communicate in writing)	Lab reports	Unit operations lab
k (ability to use techniques, skills, and modern tools)	Exams	Unit operations lab

As preliminary assessment of student outcomes, for each deliverable, the department keeps track of average performance against established rubrics. The average score against these rubrics and the number of students who pass the course but fail to meet a specific standard are documented on a semester to semester basis. The results of this assessment are used to justify changes to the course and also to observe trends in student performance.

Example Application of Assessments: Course Improvements

The first semester that student performance was assessed in this way was in Spring of 2011, and a sample of the analysis is shown in Table 4, below. This assessment was used as rationale for a number of changes for subsequent versions of the course.

The most pressing issue regarding assessment of student abilities in regarded the nature of assignments, some of which were necessarily group-based while others were completed individually. To more accurately assess individual student skills, the group sizes were reduced from 4-6 in 2011 to 3-4 in 2012, and aspects of some laboratory exercises were assigned to individuals instead of groups. To improve on the individual efforts and consistency in peer evaluations, the online Comprehensive Assessment for Team-Member Effectiveness (CATME) surveys were administered through the team-based portions of the course. An additional weekly hour of discussion was added to the course in 2012 to add the series of activities and lectures devoted to professionalism, ethics, and safety in the second half of the semester, and to provide more contact time to focus on MATLAB programming in the first half.

The nature of some assessments changed considerably in 2012. The cutoff for all assessments was raised to a 65% to be more consistent with the department-wide rubrics used to assess student abilities. The MATLAB exam was expanded to include a component that tested student ability to use a function they had never seen before. The ethics assessment was changed from a single discussion to a series of essays and a minor portion of the final exam. Lab reports were assessed electronically, so individual scores for all components of each report were recorded, for a more accurate reflection of team efforts and progression. By averaging across five laboratory experiments, we had a better sense of student ability than by selecting one report.

Table 4: Direct Assessment of Student Performance, Spring 2011

Criterion	Student work	Average score	Cutoff score	Students below cutoff	Notes
Design and conduct experiments	Hypothesis, methods, and results section of lab reports (group based)	76%	58%	0 (0%)	
Analyze data	Final exam problems (individual)	72%	58%	7 (17%)	Students perform statistical tests, regression, and dimensional analysis to show reasoning in engineering problems.
Work in Teams	Peer evaluation (individual)	92%	66%	1 (2.4%)	Based on instructor assessment using department rubric where a 6 out of 9 is satisfactory.
Solve open ended problems	Lab reports (group based)	77%	58%	0 (0%)	Students propose solution method for a general problem statement. Assessed based on grade for terminal velocity lab experiment.
Understanding of professional ethics	In-class assignment (individual)	60%	66%	21 (49%)	Students respond to hypothetical situations requiring ethic analysis. Assessed according to department-wide rubric where a 6 out of 9 is satisfactory.
Communicate in Writing	Discussion section and format and style of lab reports (group based)	78%	58%	0 (0%)	
Use modern tools and techniques	MATLAB Exam (individual)	68%	58%	7 (17%)	Students use MATLAB to represent data, perform regression, integrate differential equations, and write functions requiring numeric inputs.

Assessment of student performance against these measures continues to be used each semester to inform modifications to future versions. In Spring of 2013, the assessment was used to meet the requirements of Writing Intensive status at our institution. This required further modifying the way written communication is assessed so that one lab report is written individually, rather than by a group. The sequence of professionalism activities continues to be modified in an effort to increase the proportion of students who meet the standards in professional ethics by the end of the course. A condensed summary of student performance in 2012 and 2013 is presented in Table 5, below.

Table 5: Direct Assessment of Student Performance, Spring 2012 and 2013

Criterion	Student work	Average score	Cutoff score	Students below cutoff	Notes
Design and conduct experiments	Hypothesis, methods, and results section of lab reports	74% (s12) 73% (s13)	65%	3/6% (s12) 0/0% (s13)	Based on average grade across all lab reports. Group based.
Analyze data	Final exam problems	76% (s12) 68% (s13)	65%	12/24% (s12) 14/29% (s13)	Students perform statistical tests, regression, and dimensional analysis to show reasoning in engineering problems.
Work in Teams	CATME Surveys	78% (s12) 80% (s13)	65%	4/8% (s12) 1/2% (s13)	Based on responses to five categories in standard CATME survey.
Solve open ended problems	Lab reports	74% (s12) 74% (s13)	65%	0/0% (s12) 0/0% (s13)	Based on average grade across all lab reports. Group based.
Understanding of professional ethics	Essay assignment	76% (s12) 84% (s13)	66%	8/16% (s12) 4/8% (s13)	Students summarize an event in chemical engineering history and use ethics codes and theories to evaluate the behavior of the engineers and appropriately discuss the situation.
Communicate in Writing	Discussion section and format and style of lab reports	74% (s12) 77% (s13)	65%	3/6% (s12) 0/0% (s13)	Based on average grade across all lab reports. Group based.
Use modern tools and techniques	MATLAB Exam	72% (s12) 77% (s13)	65%	7/14% (s12) 5/10% (s13)	Students use MATLAB to represent data, perform regression, integrate differential equations, and write functions requiring numeric inputs.

Based on recent assessment, in the Spring of 2014, the individual lab report required by the Writing Intensive requirements of the course will be used in this analysis to remove the group-based analysis. Further, alternate measures for assessing student ability to analyze data on an individual basis are being considered to replace or supplement the final exam to determine whether this is an accurate way to measure performance.

Summary

Our institution has developed a novel course that combines statistical methods with experimental design in a way that students get several opportunities to practice both. Further, because of the structure of the course, students are required to apply statistical skills out of context, since the laboratory component begins after the lectures and assignments in statistics are completed. The course is located in the curriculum between courses in material and energy balances and courses in fluid mechanics and thermodynamics, to serve as a preview to later topics. The experimental design course also serves to build on student ability to use MATLAB and introduces them to topics in engineering ethics in process safety.

Student performance is evaluated against established outcomes on a preliminary basis to inform future versions of the course. In the past three years, this analysis has been used to change group sizes in the laboratory and build on activity series in professionalism and computer programming. This performance was also used to justify a Writing Intensive course designation. Performance continues to be monitored regularly to continuously improve the course.

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Appendix A – Detailed Learning Objectives

<u>Gain experience and problem solving skills associated with chemical engineering</u>

Apply degree of freedom analysis to show a chemical engineering problem has a solution.
Use degree of freedom analysis to outline a solution method for a problem, including defining open degrees of freedom.
Write a set of material and energy balances to describe a chemical engineering problem.
Balance complex chemical reactions.
Recognize a system of linear equations.
Reformulate a system of linear equations as a matrix equation.
Use the matrix determinant and rank to explain possible solutions to a matrix equation.
Use the matrix condition number to explain reliability of a numerical solution to a matrix equation.
Express a physical or chemical property in its most fundamental dimensions (length, mass, time, temperature, amount, current, luminous intensity).
Render an equation in terms of dimensionless parameters.
Apply dimensional analysis for a given system to describe what quantities could be varied to completely explore that system experimentally.
Apply similarity principles to scale up or scale down a physical or chemical process.

<u>Use computer tools including Excel and MATLAB to analyze data and construct models</u>

Enter vectors and matrices in MATLAB.
Explain the restrictions on function, file, and variable names in MATLAB.
Use MATLAB to compute the trace, determinant, rank, and condition number of a matrix.
Use MATLAB to solve a system of linear equations.
Write customized functions in MATLAB that allow for single or multiple inputs and single or multiple outputs.
Write anonymous functions in MATLAB.
Write a script in MATLAB.
Compute statistical measures (mean, variance, etc.) using Excel and MATLAB.
Use Excel or MATLAB to conduct statistical hypothesis testing on the mean, variance, or correlation coefficient for a set of data.
Use Excel and MATLAB to find the least-squares polynomial regression on a set of two-dimensional data.
Use MATLAB to construct linear and cubic splines on a set of two-dimensional data.
Numerically estimate the integral of a function or data set.
Numerically estimate the derivative of a function or data set.

Gain basic proficiency in programming elements including input/output, loops, conditionals, and array manipulation

Write a conditional statement in MATLAB.
Write a counter-controlled loop in MATLAB.
Write a condition-controlled loop in MATLAB.
Evaluate a conditional statement "by hand" to predict the output of a computer code.
Evaluate loops "by hand" to predict the output of a computer code.
Write a loop in MATLAB that uses the index of the loop as part of the repeated subprogram.
Write MATLAB codes that apply iterative methods (bisection, successive substitution, etc.) to numerically solve equations of the form f(x)=0.
Write MATLAB codes to solve an ordinary differential equation given initial conditions.
Write MATLAB codes to solve a system of ordinary differential equations given initial conditions.
Write MATLAB codes to solve a system of ordinary differential equations given boundary conditions (using the shooting method or the finite difference approximation).

Apply statistical concepts associated with experimentation, including hypothesis testing, statistical significance, and calculation of measures of central tendency, variation, and error

Construct a histogram on one-dimensional data.
Compute the mean, median, and mode of one-dimensional data.
Compute the variance and standard deviation of one-dimensional data.
Compute the z-score of a datum given a mean and standard deviation.
Compute a confidence interval on the mean of a data set given a level of significance.
Compute a confidence interval on the variance of a data set given a level of significance.
Conduct a one-sample hypothesis test to determine the probability that the mean of a sample is greater or less than a given value.
Conduct a one-sample hypothesis test to determine the probability that the variance of a sample is greater or less than a given value.
Conduct a two-sample hypothesis test to determine the probability that the mean of a sample is greater than, less than, or equal to the mean of another independent sample.
Conduct a two-sample hypothesis test to determine the probability that the variance of a sample is greater than, less than, or equal to the variance of another independent sample.
Conduct One-Way Analysis of Variance to determine the probability that the mean of a sample is different from the means of other independent sample.
Conduct Multi-Way Analysis of Variance to determine whether multiple independent factors have significant interaction in their effects on a dependent variable.
Explain how correlation and causation are related and how they are different.
Conduct a hypothesis test to determine whether two-dimensional data is statistically significantly correlated or not.
Determine the least-squares linear regression on a set of two-dimensional data.
Apply General Linear Least Squares theory to determine the least-squares nonlinear regression on a set of two- (or more) dimensional data.
Explain the differences and applications of interpolation versus regression.
Explain the differences and applications of interpolation versus extrapolation.

Develop basic skills associated with working in a group, practice leadership in a group setting, and apply tools to resolve (or avoid) conflict when working in a group

Formulate a group contract to outline individual interactions in group settings, revising the document as needed.
Serve as coordinator (leader) of a group.
Serve as recorder of a group.
Maintain consistent, sufficiently-detailed records of all group meetings.
Practice methods to keep all group members up to date on decisions (emails, document sharing, etc.).
Document all group conflicts as they arise and use the group contract to guide individual actions.

Formulate responsible and ethical responses in personal and professional settings

Demonstrate an ability to procure a code of ethics from a professional society or organization.
Explain the difference between codes of ethics, corporate policies, and governmental laws.
Apply elements from a code of ethics to evaluate actions taken by engineers in case studies.
Apply elements from a code of ethics to justify actions taken in personal hypothetical situations.
Explain the basic ideas behind at least four different ethical philosophies (utilitarianism, duty ethics, rights ethics, virtue ethics, etc).
Identify safety hazards in the laboratory.
Describe several examples of Personal Protective Equipment and when/how they should be used.
Describe application of the "action verbs" associated with industrial hygiene and inherently safe practices.

Apply the scientific and engineering methods, including hypothesis formulation and experimental design to test hypotheses, conduct experiments, collect and analyze data, and communicate results

Describe the scientific and engineering methods and the differences between them.
Formulate a hypothesis such that statistical analysis provides a meaningful result.
Design an experiment to meet a specific objective given a provided list of equipment.
Clearly communicate an experimental procedure that you developed yourself.
Conduct experiments in a laboratory environment in a safe, efficient, professional manner.
Report data to an appropriate number of significant figures.
Apply conventions of technical communication to properly display text, tables, figures, and equations in a laboratory report.

Appendix B– Sample Experiment Prompt

This is an example of a laboratory prompt for one of the first weeks of lab. Students are expected to apply two-sample hypothesis testing on the mean to demonstrate that the heat capacity of one metal is greater than the other.

Heat Capacity Experiment

Your goal in this exercise is to experimentally determine the specific heat capacity of two different metals. The specific heat capacity (or specific heat, c_p) is the amount of heat energy per unit mass required to raise the temperature by one degree Celsius. You will have one laboratory period to complete all experiments necessary. The following materials will be available for use:

an insulated container
beakers
a thermometer
a balance
water at 0°C (unlimited ice)
water at near 100°C (a hot plate)
a brass object
a steel object
thread
tongs

No other materials are allowed.

The first law of thermodynamics will be helpful to you as you think about designing your experiments. Remember (from material and energy balances) that for a closed system

$$\Delta U + \Delta E_K + \Delta E_P = Q - W$$

where the terms on the left side of the equation represent changes in energy inside the system, and the right side of the equation refers to energy that crosses the boundary between the system and the surroundings. The equation is written on a *per mass* basis.

Also recall that $\Delta U = c_v \Delta T$, and that for liquids and solids $c_v \approx c_p$.

Appendix C – Rubric for Assessing Lab Reports

Experimental Objective and Hypothesis _______ (10%)

Objective clearly stated.
Posed hypothesis is testable.
Hypothesis is relevant to objective/laboratory assignment.
Hypothesis is not trivial.

What would make this section stronger:

Methods _______ (10%)

Methods are clearly described; someone outside ENCH 225 could repeat the experiment.
Materials are listed. Materials are used in a safe way during experiment.
Methods are appropriate for the given materials.
Experiment is relevant to the hypothesis.

What would make this section stronger:

Results _______ (30%)

Appropriate observations were made and appropriate data were collected.
Data are presented in a meaningful way.
Organization of data sheets and sample calculations aids in clear understanding of results.
Experimental uncertainty is appropriately handled.
Appropriate data analysis is performed - and done correctly.
Calculations are free from error and incorporate appropriate units and significant figures.
Sufficient detail is given so the accuracy of data analysis can be confirmed independently.

What would make this section stronger:

Discussion and Conclusions _______ (20%)

Discussion of results is clear, well organized, and exhibits the right amount of detail.
Discussion demonstrates thoughtful consideration of the experiment.
Discussion indicates bearing of results on the experimental hypothesis.
Discussion adequately explains experimental uncertainty and error.
Discussion sufficiently relates experimental results to relevant findings in literature (references).

What would make this section stronger:

Report Format and Writing Style _______ (30%)

Report is clean and efficient.
Report is free from typographical errors.
Report is free from grammatical errors.
Writing style is appropriate for a technical report:

    Level of sophistication in writing is appropriate.
    Sentence structure aids in smooth reading of report.
    Correct use of verb tenses is employed.

References are carefully chosen and cited properly in a logical location in the report.
Figures, tables, and equations are prepared properly and introduced in the report.
Captions for figures and tables are appropriate in description and position.
Report can be easily read with no loss of meaning or clarity if copied/printed in grayscale.

General Comments: