Chemical Engineering
Unit Operations
Laboratory Manual

Department of Chemical Engineering

Rowan University

(rev 1/14/10)

Spring 2010

Unit Operations Lab
CHE06.404

GENERAL INFORMATION

INSTRUCTORS:

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MEETING TIME & LOCATION:
The course meets every Wednesday 3:15 PM – 7:30 PM. Students are expected to be on time and prepared unless prior arrangements have been with the following parties:

- Faculty member in charge of the experiment
- Graduate student responsible for the experiment
- Other group members

Course lectures and oral reports will take place in 340 Rowan Hall. Laboratories will take place in the 3rd floor laboratory space in different bays depending on the experiment.

COURSE OBJECTIVES:

1. Understand and apply engineering experimentation techniques and safety procedures common to the chemical industry.
2. Apply principles developed in chemical engineering courses to the analysis of chemical engineering processes and unit operations.
3. Improve technical writing skills.
4. Improve skills necessary for group work—interpersonal skills, coordination of the efforts of several persons, leader and subordinate roles, etc.

COURSE PROTOCOL:

Four projects (four experiments) will be carried out during the semester. Students will work in groups of 3-4. There will be a project leader for each project. This position will rotate throughout the semester. Each project will require either an individual or group report (written or oral).

It is fairly easy to obtain copies of previous experimental reports. But please do your own work as an individual and on your team. No plagiarism of laboratory data or reports will be tolerated. Such actions will result in academic misconduct charges being brought against the student.

The project leader is responsible for assigning tasks during the experiment and for assigning tasks for completion of the group report. The final grade for the course is made up of lab preparation presentation grades, lab report grades and lab performance.

Please come prepared to the laboratory with a full understanding of the experiment details and the purpose of the experiment. Know which data you are going to collect, and agree upon the different roles of the team members, to make adequate progress. Be ready to answer questions asked by the Professors or Graduate Students regarding the experiments.

Everyone must read the safe laboratory operating guide. Everyone must sign and turn in the attached testament on page 12 of this document.

Before an experiment can be run, each team must present to the faculty an understanding of the experiment and its hazards. The form is located on page 13 of this document.

GRADING:

TASK	Maximum possible points per task	Type, number	Absolute maximum possible points
Lab Readiness Presentations+	10 points	Individual, group (3)	40 points
Lab Report 1(short)	80 points	Individual	80 points
Lab Report 2(long)	120 points	Group	120 points
Lab Report 3 (Oral Report)	100 points	Group	100 points
Lab Report 4 (long)	120 points	Group	120 points
Professional Conduct	40 points	Individual	40 points
TOTAL*			**500 points**

(+) Theoretical knowledge, command of experimental protocols, and lab datasheets.

SAFETY VIOLATIONS

All students will adhere to the laboratory safety rules. Any unsafe practice will result in a deduction of up to 10 points from the final report grade of the lab experiment during which the violation took place.

LAB READINESS ASSESSMENT PRESENTATIONS

Before beginning an experiment, each member of the team must be familiar with the equipment and well versed in the theory behind the experiment. To facilitate preparedness, each team will prepare a 5-10 minute presentation that explains the theory and equipment used for each experiment. All groups will present on the same Wednesday prior to the start of a new set of labs. These presentations are intended to spark dialogue between groups regarding the operation and analysis of each lab. In addition, the team must have a “Pre-Experiment Approval Form” signed by Professor Slater, Professor Gould or Professor Grady before starting the experiment.

LAB REPORTS

Each group/individual will conduct 4 lab experiments and do four reports. One of these reports will be *individually written,* short, executive summary style reports of no more than three or four pages (not including appendices). Grading criteria style for these reports will be provided and discussed in class.

For two reports, the team will have the opportunity to address the material more thoroughly, and more in-depth discussion of theory and results will be required. The long reports should be ten to fifteen pages in length. Each team member will be responsible for a section or sections, as assigned by the group leader for that experiment, and should indicate who wrote that section in the report. Reference materials will be available on reserve in the library for all experiments, and should be consulted for the long reports in particular.

The remaining lab report will be presented orally using Powerpoint slides (this will represent the written report). It should cover those topics addressed in the "executive summary" style report since it is limited to 15 minutes in length. The group (all group members) should be prepared to answer any question that a faculty member may pose, from theory to the equipment used and results obtained.

Lab reports are due on the Wednesday at 3:15 pm following each lab experiment. Lab reports will be graded and usually within one or two weeks, and faculty will provide detailed comments at that time

Laboratory Report 1: Short, individual
Laboratory Report 2: Long, group
Laboratory Report 3: Oral, group
Laboratory Report 4: Long, group

Communication skills are an important part of an engineer's career and as such we will take extra time to critique your first short, individual report. Please use those comments to improve your writing for subsequent reports.

Spring 2010 Schedule of Experiments*:

Date	IV Shell and Tube Heat Exchanger	VI Packed Tower Gas Absorption	XV Filter Press	XIII Reverse Osmosis
1/20	Course Intro			
1/27	Pre-Lab Presentations			
2/3	A1 Short	A2 Short	A3 Short	A4 Short
2/10	B4 Short	B3 Short	B2 Short	B1 Short
2/17	Pre-Lab Presentations			
2/24	A2 Long	A3 Long	A4 Oral	A1 Oral
3/3	B3 Oral	B2 Oral	B1 Long	B4 Long
3/10	Oral Presentations and Pre-Lab Presentations			
3/17	Spring Break			
3/24	A3 Oral	A4 Long	A1 Long	A2 Oral
3/31	B2 Long	B1 Oral	B4 Oral	B3 Long
4/7	Oral Presentations and Pre-Lab Presentations			
4/14	A4 Long	A1 Long	A2 Long	A3 Long
4/21	B1 Long	B4 Long	B3 Long	B2 Long
4/28	Wrap-up			

*Order of experiments is subject to change, depending on state of equipment and availability of utilities.

Team Assignments:

A1	A2	A3	A4	B1	B2	B3	B4
Baals	Manaresi	Hankins	Kosteleski	Kostetskyy	Burke	MacGregor	Hodges
Batten	Whitaker	Lussier	Iftikhar	Sattler	Lowe	OConnor	Martarano
Jamison	Zienowicz	Tomaino	McIver	Vliet	Salvetti	Schiavi	Sokal
Osborn							Weigand

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Safety in the Laboratory

Good laboratory technique is not only the mark of professional pride but also enables you to avoid most accidents. Good techniques include proper handling of chemicals, glassware and apparatus, and the knowledge of, and habitual use of, safety precautions.

GENERAL SAFETY RULES

1. The written approval of the instructor is required for anyone to be in the laboratory after hours, on weekends, or on non-scheduled laboratory days.

2. No equipment is to be operated until the approval of the instructor has been obtained at the start of class. Only the equipment pertaining to the assigned experiment is to be operated. All members of a group are to be properly informed on the safety aspects of their assigned experiment and to be familiar with the safety aspects of surrounding experiments

3. Safety glasses with sideshields or safety goggles (when handling hazardous chemicals). Neckties, dangling clothing or jewelry, and other unsafe items are prohibited. Long pants are recommended.

4. Sleeping is prohibited in the laboratory. Violation of this rule will result in dismissal from the laboratory for that day and an unexcused absence.

5. Horseplay of any sort is absolutely prohibited in the laboratory.

6. Smoking and open flames are prohibited in the laboratory.

7. The safety precautions in the experimental plan must be followed.

8. No operating equipment will be left unattended. At least two members of the group must be present while the equipment is operating.

9. The laboratory floor must be kept dry, clean, and uncluttered at all times. Any spills should be cleaned up immediately.

10. All chemicals must be transported in a safety carrier. All mercury and alcohol thermometers and more than one item of glassware must be transported in a bucket or other suitable container.

11. CHEMICALS AND GLASSWARE ARE NOT TO BE TRANSPORTED ON THE SPIRAL STAIRCASE. Only notebooks, calculators, pens and small tools are allowed to be carried on the spiral staircase.

12. The students are expected to be familiar with the safety aspects of all the chemicals used in the laboratory and with the coding system used to label containers and pipelines.

13. Any accident or hazardous situation must be reported to the Laboratory Supervisor immediately.

14. Any "serious" violation of any of these safety rules may lead to immediate dismissal from the course. "Minor" violations of any of these rules will be dealt with in a manner consistent with the Safety Program. A person who repeatedly disregards the safety rules will be called in for consultation with one of the laboratory safety coordinators. A penalty that suits the violations may be imposed and, at the discretion of the Unit Operations Laboratory Faculty Committee, the student's grade may be lowered.

PERSONAL PROTECTIVE EQUIPMENT

Personal protective equipment shall be provided, used, and maintained in a sanitary and reliable condition whenever it is necessary by reason of process or environmental hazards.

1. DUST MASK
   A. A dust mask should be worn when handling powdery solids.
   B. Dust masks prevent inhalation of solid particles.

1. EAR PROTECTION
   A. Earplugs protect the ears against high-decibel noise (90 dBA or above).
   B. If your ears are sensitive to noise, you may want to wear earplugs while working in laboratory.

3. EYE PROTECTION
   A. Safety glasses with sideshields or safety goggles are to be worn at all times in the laboratory.
   B. Safety goggles must be worn when handling hazardous chemicals.
   C. Contact Lenses are discouraged in the laboratory. If contact lenses are worn, safety goggles are strongly recommended in place of safety glasses with side shields.

4. FOOTWEAR
   A. The following footwear are not allowed:

1. Ventilated shoes.
2. Sandals.

B. The following shoes are not recommended:
1. Porous leather or cloth shoes.
2. Tennis shoes.

C. Proper footwear is required to protect the feet against burns from chemicals, steam, and hot water. Use good judgment.

5. GLOVES
A. Insulated gloves are required to avoid burns when operating steam valves and when handling hot objects.
B. Rubber or other protective gloves are required to avoid contact with chemicals that can burn or penetrate the skin.

6. REQUIRED CLOTHING
A. Long pants (recommended).
B. No neckties, no dangling clothes nor dangling jewelry.
C. Buttoned long sleeve shirts (recommended).
D. Precautions should be taken to prevent long hair from becoming entangled in moving machine parts.
E. Long-sleeve laboratory coat when handling chemicals that can burn the skin or be absorbed through the skin.

7. LOCATION OF PERSONAL PROTECTIVE EQUIPMENT
A. Dust masks, ear plugs, and gloves are in the Laboratory.
B. Goggles can be purchased from the Rowan University Bookstore.

GENERAL EQUIPMENT SAFETY

1. CHEMICAL SAFETY
A. A safety carrier is available in Chemistry Stores.
B. Transport <u>all</u> chemicals using a safety carrier. The chemical must be in a closed container.
C. NO CHEMICALS are to be carried on the spiral staircase. Use the elevators or alternative stairways.
D. Flammable, volatile chemicals are to be stored in the Flammable Liquids Storage Cabinet.
E. Chemicals are NOT to be stored in the hoods. Chemicals must be removed from the hoods at the end of the day.
F. Use a Class B Fire Extinguisher for chemical fires.
G. All containers must be labeled as to their contents and must have a “Right to Know Law” Label attached. Any unlabelled container must be reported to the Laboratory Supervisor and be treated as a hazardous substance.
H. Wear protective gloves and apron when handling strong acids and bases.
I. The Laboratory Supervisor must be notified of any new chemical introduced into the laboratory so that the MSDS can be obtained and all students can be trained on the handling of the chemical.

2. CHEMICAL STORAGE CABINET
   A. No flammable, volatile chemicals are to be stored.
   B. Store acids and bases on the lowest shelf with acids on one side and bases on the other side.
   C. Store oxidizable materials away from acids and bases.
   D. ALL chemicals must be labeled.
   E. The Laboratory Supervisor must be notified of any new chemical placed in the chemical storage cabinet so that the MSDS can be obtained and the chemical list updated.

3. ELECTRICAL SAFETY
   A. Use the “left-hand” rule in operating power boxes, i.e. use the left hand to move the handle up or down.
   B. Power must be off before making electrical connections.
   C. Avoid splashing or spraying water on electrical connections, wall sockets, and junction or power boxes.
   D. Keep extension cords away from traffic and water.
   E. Use 3-pronged plugs with a ground connection.
   F. Use a Class C Fire Extinguisher if energized electrical systems are involved.

4. FLAMMABLE LIQUIDS STORAGE CABINETS
   A. Only flammable chemicals should be stored here.
   B. Separate non-compatible chemicals.
   C. ALL chemicals must be labeled.
   D. The Laboratory Supervisor must be notified of any new chemical added to the Flammable Liquids Storage Cabinet so that the MSDS can be obtained and the list updated.

5. FLAMMABLE WASTE CONTAINER
   A. Solid flammable waste should be disposed of in the Flammable Waste Container.
   B. Located in the Unit Operations Laboratory.

6. GAS CYLINDERS
   A. Cylinder contents are under pressure; keep cylinders upright and secured to a sturdy base with a chain.
   B. The gas or liquid contained in the cylinder should be clearly identified on the container.
   C. If a cylinder has been emptied, clearly label this information on the container.
   D. Keep the valve cover screwed securely on top of the cylinder while storing.
   E. Store cylinders away from high temperatures.
   F. Do not store flammable materials near oxygen cylinders.
   G. Always move a cylinder tank with a cart; cylinder must be chained to the cart and valve cover screwed on.
   H. Have the Laboratory Supervisor or maintenance personnel change cylinders.
   I. Once the cylinder is installed:

1. Make sure connecting pipes and hoses are tight and in good condition to prevent leakage.
2. Check for leaks with soapy water.

J. Fully open main cylinder valve.

7. GLASSWARE
   A. Glassware is not to be transported up or down the spiral staircase. Use the elevators or stairways.
   B. Glassware and mercury or alcohol thermometers must be transported in a bucket or suitable container.
   C. Use hand protection when inserting glass tubing into rubber stoppers, corks, or rubber tubing.
   D. Glass tubing should be fire polished and lubricated before insertion into rubber stoppers or rubber tubing.
   E. Always wear eye protection when using glassware.
   F. Take care in storing and in handling glassware.
   G. Discard or replace damaged glassware.
   H. Use only vacuum designed glassware for vacuum purposes.
   I. Dispose of broken glass in the broken glass container.

8. LADDERS
   A. Ladders are always to be chained when not in use.
   B. When one or more ladders are in use, the remaining ladders should be chained. A hook on the chain makes it possible to chain the ladders without locking the chain.
   C. Do not use the top two steps and do not lean while using a ladder. Someone should hold the base of the ladder while it is being used.
   D. Avoid lights and electrical wires while moving a ladder.
   E. Moving ladders longer than 6 feet requires two people.

9. MANOMETERS
   A. By-pass valve must be open before opening valves in lines to manometer legs.
   B. Open valve to low pressure source first and then valve to high pressure source.
   C. Close by-pass valve slowly and observe manometer reading. If manometer level is going off-scale, quickly open by-pass valve.
   D. Open by-pass valve immediately after taking the reading.
   E. Close valve to high pressure source first and then valve to low pressure source.

10. MIXING AND STIRRING DEVICES
   A. Keep hands, hair, and loose clothing away from agitator.
   B. Lock out the power supply to the agitator before adding material to the tank or before manually stirring the material in the tank.
   C. For hand-held agitators, make sure agitator is off before adding material to the tank.
   D. If solids have settled to the bottom of the tank, they should be stirred by hand before starting the agitator.

E. Make sure the agitator is immersed in the solution to be mixed before starting motor.
F. Turn off motor before removing the agitator from the mixed solution.

11. PERSONAL HYGIENE PRACTICES
    A. Wash hands before and after running an experiment.
    B. Wear gloves appropriate for the experiment. Clean the gloves after using them.
    C. Cover any cuts or open wounds with clean, suitable material.
    D. Do not apply cosmetics while in the laboratory.
    E. Keep extra clothing available so that you can change after working in the laboratory or in case your clothes become contaminated.
    F. Use a pipette bulb; do not use your mouth to pipette.

12. PUMPS, FANS, BLOWERS, AND COMPRESSORS
    A. Make sure that guards on moving parts and on electrical connections are in place.
    B. Keep clothing, hands, and hair away from moving parts.

13. RADIOS AND WALKMANS
    A. Listening to radios and walkmans is prohibited in the laboratory.

14. SAFE LIFTING PRACTICES
    A. Clear a pathway before moving things.
    B. Check the object's weight to see if help is needed.
    C. Keep back straight and vertical to the ground. Keeping your head up and looking straight ahead will help.
    D. Bend knees when lifting; use the legs to lift and not the back.
    E. Bring the object as close to the body as possible.
    F. Be careful when putting the object down; follow the same guidelines as for lifting.

15. STEAM LINES AND CONDENSATE LINES
    A. Use insulated gloves for operating steam valves.
    B. Open valves slowly and only to the desired amount.
    C. Keep hands and clothing away from steam lines.
    D. Lines from steam traps should extend into the drain.
    E. During initial start up, by-pass steam traps until live steam exits from discharge line.
    F. Stay clear of condensate/steam discharge lines, especially during initial start up.

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I have read the Laboratory Safety section of the U.O.L. manual and understand the contents. I shall conduct myself in a safe and professional manner during the time I am in the laboratory and shall notify the Instructor of any unsafe condition that comes to my notice.

Date: ________________ Signature: _______________________

Printed Name: ____________________

PERMISSION TO START EXPERIMENTATION

Experiment Subject/Title:____

Experiment____
date time

Operating procedures approved by (initial if OK): **INSTRUCTOR**

startup	____________
data collection	____________
shutdown	____________
emergency shutdown	____________

Preliminary report submitted ______________
date

Assignments:	**Student Responsible:**
data collection plan	_________________________
safety	_________________________
operating procedures	_________________________
data collection/recording	_________________________
calibration procedures/data	_________________________
theory	_________________________

Potential electrical hazards ☐ **yes** ☐ **no** If **yes**, identify location:
____
____

Potential mechanical hazards? ☐ **yes** ☐ **no** If **yes**, identify location:

Required chemicals/physical state/purity/amounts:
____
____
____
____

MSDA reviewed ____
signature of safety director for group/team date

Hazardous/toxic chemicals involved? ☐ **yes** ☐ **no** identities:
____
____
____

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Written Report Guidelines

Report Format:
You will do 4 reports this semester: 1 will be individually-written short, executive summary reports of no more than 3 or 4 pages (not including appendices), 2 will be longer (full-length) 10-15 page reports that will be written as a group. 1 will be an oral report. The shorter, individual reports, do not have every element and can include abbreviated elements as needed. It is expected that the longer, group reports, will include every element.
The object of each report is to present data in a clear manner that can readily be understood by your peers, instructors and future employees. The reports should usually be written in the third person, and the tense, at least in any single paragraph, should be consistent. Grading guidelines for each report are included to help you understand the criteria for each report.

1. Full-length report

10 pts

Letter of Transmittal

Title Page including Abstract *** Required for Short Report ***

Report title with date, names, etc.
1 or 2 paragraph synopsis of the experiment, results, and conclusions.

Table of Contents

List of Sections
List of Figures
List of Tables

25 pts

Introduction/Background

Hypothesis of the experiment, *** Required for Short Report ***
Theory/basis for the experiment,
Others work in the area.

Summary and Conclusions

Executive summary of the experiment.
Do the results support the hypothesis?
What conclusions can you draw from the experiment?

Experimental

15 pts — A detailed description of experiment including analytical methods. (This is not the lab write-up, more like a journal submission)

Results and Discussion

30 pts — In-depth analysis of the data.
Discussion of the data relative to the hypothesis. *** Required for Short Report ***
Discussion of the conclusions drawn.

Recommendations for Improvements

10 pts — What can be done to improve the experiment? *** Required for Short Report ***
What should the next group do to get a better result?

Appendix *** Required for Short Report ***

10 pts — Supporting data/tables/figures.

Sample Calculations (as needed, representative of the data analyzed. Presented in a form that we can understand and follow, like posted faculty solutions to homework)

2. Executive Summary (Short Report)

In laboratory reports #1 individuals will submit a short, executive summary-style report of no more than 3-4 pages.

This report should include:

- A brief summary/abstract that includes the objective of the experiment, key results and recommendations (this section summarizes the rest of the documents)
- Results (required report items).
- Conclusions and Discussion.
- References (not counted in the three-page limit).
- Appendix (not counted in the three-page limit): This may include other information such as additional figures, tables, error analysis, that is not included in the narrative.

See the grading template for the Memo report that provides more details on content.

3. Oral Reports

The oral reports will be presented by the group and each group member is expected to participate in the presentation. These oral reports should be presented in a style that you use for your Engineering Clinic presentations (using MS Powerpoint) and cover those parts of the Executive Summary as outlined above for the Short Report.

- A brief introduction that includes the objective of the experiment
- Results (key results that you would include in a Short report).
- Discussion of results
- Conclusions including recommendations on improving the experiment

The presentations will be graded on both technical merit and quality of the presentation. Instructors will ask students questions at the end of the presentation. Each group member is responsible for knowing all aspects of the experiment, from theory, equipment, results, etc. The oral reports should not exceed 15 minutes in length.

Some general report guidelines (applicable to both types)

Graphs: Graphs should be generated by a computer graphics program. The variables or functions plotted on the axes as well as any parameter should be shown with the units designated.

Like drawings, graphs should be complete in themselves, i.e., their full meaning should be evident without reference to the remainder of the report. Thus, all graphs must have a figure number, and an explanatory legend. If more than one curve is drawn on a single graph, each one must be clearly labeled. When different symbols (circle, square, etc.) are used to label multiple curves on one graph, define the symbols in a key. Colors may be used to differentiate different curves but must be suitable for black and white copies (i.e., light grey and dark gray/black).

Equations: All equations should be generated using Microsoft equation editor, centered, and numbered (with the equation number flush with right-hand margin).

Note: All equations, tables and figures presented throughout the report are to be numbered.

Grading Sheet: Short (Executive Summary) Report

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Summary (10 pts) Abstract (Purpose, Parameters investigated, Key results, etc)	
Required items completed (15 pts) (see lab write-up) Graphs, Tables, Correlations, etc	
Adequate data (15 pts) Data gathered in appropriate range and sufficient data taken? Graphical technique	
Explanation/Justification (25 pts) Discussion/Hypothesis/Conclusion/ Are data/results reasonable? What do your results mean? Do results compare with literature?	
Computer work (5 pts) (In appendix)	
Sample calculations (20 pts) Error analysis (when required) (In appendix)	
Appendix & References (5 pts) Clearly labeled & organized Referenced appropriately in text	
Organization & Presentation (5 pts) Easy to read, looks professional Graphs & charts integrated into text	

Check List for Lab Reports – ChE06.404, Unit Operations Laboratory			
		Yes	No
General			
A	Appropriate report length		
B	11 or 12 point type, single spaced		
C	Handed in on time?		
D	Spelling and grammar checked?		
E	Design question(s) answered		
F	Group Identified properly, name on report		
Graphs			
G	Is each graph numbered?		
H	Graphs fully and clearly labeled		
I	Graph axes labels useful (no furlongs per fortnight)		
J	Are the units included for each axis?		
K	Are data points differentiated well?		
L	Line through the points		
M	Are calculated or theoretical lines shown without data points?		
N	Is the line of the proper type? (Straight vs. curve?)		
O	If the slope is shown, does it make sense and is it necessary?		
P	Even decades for a log-log plot		
Q	Is the graph big enough to see easily?		
R	Are different data series shown clearly?		
Charts			
S	Graphs and charts numbered		
T	Charts titled clearly		
U	Each column clearly labeled		
V	Significant Figures		
Equations			
W	Symbols for equations defined		
X	Equations editor used		
Y	Equations centered and numbered (with number right-justified)		
Summary/Abstract			
AA	No more than two paragraphs		
BB	Includes the purpose, the experimental technique, the range of the parameters investigated and the main results.		

Appendix A:
Data Analysis

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Data Analysis

Experimental measurement is a basic and important facet of engineering, and thus engineers must be familiar with the methods of measurement, their accuracy and limitations, and the effects of measurement error or uncertainty on subsequent calculations. The following is a brief presentation of a number of important factors in data analysis.

All experiments involve measurements of physical properties. Measurements of different properties, or of the same property with different instruments, or by different persons, are made with varying degrees of accuracy and precision. It is important when considering or communicating measured values to be able to specify the measurement uncertainties. The measurements themselves are seldom the ultimate objective of actual experimental engineering projects. Instead, calculations are performed using these measured values, and the calculated results thereby also have some uncertainty associated with them. This uncertainty must also be determined. Finally, the results of the experimental project are often used to develop a correlation. The statistical validity of the correlation is also an important result of the project, and must be known and understood by the engineer.

The types of experimental error are described by H. D. Young in excerpt #1, pp. 2-3. Note the distinction between accuracy and precision in experimental measurement, and their relationship to systematic versus random errors. Almost all-statistical analyses of experimental data assume the errors (or more correctly, the uncertainties) in the measured values to be of a random nature. Thus, for the statistical analyses to be valid, it is important that systematic errors be eliminated, else they will bias and invalidate the treatment. Elimination of systematic error can best be accomplished by a well planned and well executed experimental procedure. Systematic errors caused by incorrect instrument calibration can be eliminated by checking the calibration. Systematic errors caused by incorrect reading of instruments can be caught by a second person reading the instrument. In many cases, systematic error can be eliminated by thoughtfully examining data as it is collected (rather than simply recording the data for later computation) and thus identifying 'jarring' measurements which point to hardware or operator inconsistencies. This is good experimental procedure.

When a large number of measurements are made of a physical property, statistical methods yield quantitative measures of the validity of the measures (e.g., the standard deviation). A number of these calculations are discussed in sections A. - D. of excerpt #2 by Gordon and Ford (pp. 481 - 485). These methods allow quantitative evaluation of the uncertainty in a measured value.

When the uncertainties in the measured values are known, the uncertainties in calculated values can then be determined. A simple analysis of the propagation of uncertainties through calculations is given by Holman in excerpt #3, sections 3-3 to 3-5 (pp. 48 - 59). As noted by Holman, this type of calculation is particularly useful in pointing out the most significant sources of uncertainty in the final calculated result, and therefore highlighting the weakest areas of the experimental plan. This type of analysis also enables us to determine what uncertainties are allowable in each of the individual quantities, given a specified maximum uncertainty in the final result. (Such a specification is not uncommon -- e.g., you may be requested to determine, within ± 2%, say, the cooling water flowrate necessary to cool a reactor product stream to 100°C. What measurement uncertainty is then permissible in determining temperatures and flowrates? This may determine the type of measurement device and the number of measurement replications necessary).

Note that, in practice, we are usually not free to make sufficient replicate measurements to determine the standard deviations to use as the quantities w_i in equation 3-2 of Holman. In this case, the quantities w_i are chosen to represent the best estimate of the maximum error associated with the measurement of the quantities x_i. These values are often quoted by vendors as, e.g., "± % of full scale." In other cases, no statements of maximum measurement error are provided. In this case, the engineer must provide the estimate based on such factors as intrinsic fluctuations in the instrument reading, graduation of the instrument, etc. This requires good judgment and knowledge of the experimental techniques and conditions. (Note: it goes almost without saying that numerical values should not be reported with more figures than are truly significant, significant figures being, of course, those figures "known with certainty, plus the first digit whose value is in doubt" [Gordon and Ford, p. 481]).

Finally, it is often desired to develop a correlation between some final important result and some independent variable of the experimental project. The most common method for developing such a correlation is the method of least squares. Packages for performing the correlation are available on computers and calculators, so such correlations are easily performed. It is important that the engineer understand the method and meaning of the correlation, however, and the significance of the correlation coefficient which quantifies the 'goodness of fit' of the data to the form of the desired mathematical function. The value of the correlation is discussed by Young in excerpt #1 pp. 126 - 132).

Analysis of the collected data and calculated results is a necessary component of any complete experimental project. This handout and the excerpts are intended to be a brief introduction to (or review of, depending on your experience) data analysis techniques and are not intended to be an exhaustive list or limitation of the available techniques. Perhaps the most important contribution demanded of the engineer in any project is sound engineering judgment -- common sense.