Pilot-Scale Laboratory Instruction for ChE:

THE SPECIFIC CASE OF THE PILOT-UNIT LEADING GROUP

Anne-Marie Billet, Séverine Camy, Carole Coufort-Saudejaud
University of Toulouse • Toulouse cedex 4, France

Laboratories are considered a fundamental part of the student's educational experience in engineering. In the case of chemical engineering, students implement theories and concepts that are related to mass, heat, and momentum transfer. From an educational point of view, Feisel and Rosa[1] have listed the main 13 objectives of engineering instructional laboratories: 1) instrumentation practice, 2) identification of models, 3) conducting experiments, 4) data analysis, 5) design application, 6) learning from failure, 7) use of creativity, 8) improvement of psychomotricity, 9) safety consideration, 10) efficient use of communication, 11) teamwork experience, 12) consideration of ethics (for lab), and 13) sensory awareness. During the lab session, students are usually divided into small groups, and perform laboratory or pilot-scale unit operations experiments under the direction of professors or associate teachers. Students sometimes content themselves with following the steps that are described in the protocol they have been given and do not try to deeply understand the underlying phenomena. This kind of behavior is often said to be a "cookbook" or "follow the recipe" approach, as pointed out by McCreary, et al.[2] and Young, et al.[3] As a consequence, students lack motivation for practical work and this leads to poor output, *i.e.*, to inefficient teamwork (as students are not eager to take on responsibilities) and rather poor analysis of the experimental results, among other undesirable outcomes. Assuming such behavior, the objectives suggested by Feisel and Rosa[1] are far from being fulfilled. To attempt to correct the deficiencies of such teaching, increase retention of knowledge, and improve integration of concepts, different types of laboratory instruction have been suggested. In his review, Domin[4] distinguishes four different styles of teaching (expository, inquiry, discovery, and problem-based) that can be differentiated according to three distinct descriptors (outcome, approach, and procedure). He concludes that the differences

***Anne-Marie Billet** completed her engineering degree and her Ph.D. thesis in process engineering at* "Institut National Polytechnique" *in Toulouse (France) in 1992. She is now an associate professor in the Engineering school (French 'grande ecole') INPT-ENSIACET (Toulouse, France), in the Chemical Engineering Department. She carries out research activities at the* Laboratoire de Génie Chimique *(Toulouse, France) in the field of hydrodynamics and mass transfer in bubble reactors.*

***Séverine Camy** obtained her undergraduate degree and M.S. in chemical engineering in 1997 and her Ph.D. in chemical and process engineering in 2000, from the* Institut National Polytechnique de Toulouse *(INPT). She joined ENSIACET at the University of Toulouse as an associate professor in 2006. She carries out her research at the* Laboratoire de Génie Chimique *in Toulouse on the topic of supercritical CO_2 separation and reaction processes.*

***Carole Coufort-Saudejaud** completed her engineering degree in 2001 and her Ph.D. in chemical engineering at the* Institut National des Sciences Appliquées *(INSA Toulouse, France) in 2004. Since 2006, she is an associate professor of chemical engineering at* Ecole Nationale des Ingénieurs en Arts Chimiques et Technologiques *(Toulouse, France). Her research interests are the analysis and the optimization of fluidized bed chemical vapor deposition processes at the* Laboratoire de Génie Chimique *(Toulouse, France).*

between styles lead to different learning outcomes. In a more pragmatic point of view, Birol, et al.,[5] suggest that cross-course projects can be followed; Jimenez, et al.,[6] propose to focus on open-ended problems within a "stop and go" course organization—a method that requires students to search for information, to plan experiments, to interpret data, and to derive conclusions. Doskocil[7] recommends combining the design of experiment techniques with a current experiment to present a more "real world" situation to the student. Felder and Brent[8] enthusiastically promote active learning. Based on the game show "Survivor," Newel[9] also recommends a method for active learning that addresses students' involvement. From the literature on chemical engineering laboratory education, one can see that most of studies are devoted to points 1 to 9 in Feisel and Rosa's list while the four last points—which are related to communication and management—are scarcely tackled. As pointed out by Jones,[10] Smith,[11] and Johnson and Johnson,[12] however, generic skills such as team management and time management should not be taught only during key-note lectures; they also have to be experienced first-hand.

Lab work dedicated to chemical engineering practice at INP-ENSIACET is traditionally performed in a specific platform that gathers various chemical engineering pilot-scale rigs (<http://aigep.inp-toulouse.fr/pages/page_accueilpag.html>) such as: batch and continuous distillation, liquid-liquid extraction, batch reactor, stirred tank with gas-liquid mass transfer, multiple effect evaporator, gas absorption columns, and heat exchanger. The objective of this lab experience is to have students discover and operate the instrumentation and equipment related to the main chemical engineering operations. Traditional lab practice, however, has shown some weaknesses when derived through the traditional laboratory instruction and this has prompted some instructors to propose an innovative process for managing laboratory instruction. As a result, the idea of a "pilot-unit leading group" for the chemical engineering pilot-scale laboratory instruction was introduced.

The aim of this paper is thus to present the pilot-unit leading group approach that teachers of INP-ENSIACET have put into practice for chemical engineering laboratory instruction.

PRESENTATION OF THE CONCEPT AND PRACTICE OF PILOT-UNIT LEADING GROUP

The students involved are in the second year of INP-ENSIACET engineering formation (Chemical Engineering Department); this corresponds to the first year of a Master's program. Students spend six full days in the pilot equipment platform. To ensure that the students fully benefit from these six days, technical and pedagogical booklets are given to them a few days before the beginning of the lab session. Students are expected to read them, to recall the specific theory that they have been taught on the subjects, and to bring with them any documents that may be helpful during the lab session.

Pedagogic Objectives

The pilot-unit leading group approach has a dual purpose:

1. The first is rather classical and aims at integrating the concepts learned in the classroom into a coherent learning activity,

2. The second aims at adding some communication and management skills into the curriculum. The difficulty of this dual approach is integrating the second objective without withdrawing the requirements of the first objective. As pointed out by Box, et al.,[13] one way to fulfill this goal is to include a shift in the control and responsibility of learning from teacher to student, and to promote active participation by the learner. To create such a dynamic learning environment, the educational team at INP-ENSIACET decided to transfer or partially delegate the responsibility of instruction for the pilot-units to the students and let them manage their classmates.

At the end of the laboratory session, the assessment must show that students:

- *have identified and applied relevant chemical engineering theory to the apparatus,*
- *have conducted an extensive and detailed investigation of the pilot plant operation,*
- *have gathered, carefully examined, and interpreted the data,*
- *have drawn consistent conclusions,*
- *have made recommendations based on technical and scientific aspects, and*
- *have developed skills in writing technical reports, oral and written communication, management of groups, and teamwork.*

Practical Organization

The class is divided into six groups of three or four students who work on six pilot-scale operations: liquid-liquid extraction, continuous distillation, batch distillation, absorption, stirred tank, and multiple effects evaporator. Each student group uses each pilot during one day. The pilot-unit leading group concept refers to the fact that the students become the "managers" for the pilot they have been working on during the first day of the laboratory session. As managers, they must decide which kind of experiments have to be done by the other students during the lab session, manage the other students in terms of the fixed time schedule, and answer the technical questions of their classmates.

To illustrate this concept we chose to focus on the example of a liquid-liquid extraction pilot-scale laboratory that uses water as a solvent to extract acetone from an acetone-cyclohexane mixture. The process is quite simple and consists of a 4.5 m height glass pulsed column, two feeding pumps for the solvent and the acetone-cyclohexane mixture, a pump to ensure pulsation inside the column, and several tanks for the feeds, extract, and raffinate. Students are expected to measure flow rates and the composition of the different phases using gas chromatography (GC) analysis.

Schedule of the Formation

Day 1

On the first day of the laboratory, a teacher presents the pilot-scale installation that the students have to operate. The main possible experiments that can be performed on the installation are explained. During this day, the students become familiar with the pilot plant. They analyze the apparatus and environment (instrumentation, process control, devices, analytical techniques, etc); then they perform experiments, interpret the experimental results, and put into practice both design models and tools of simulation to better understand the physical and chemical phenomena. In addition to learning the pilot operation, students spend the day in coordination with the teacher answering the different questions that arise such as:

- *How long will it take to reach a steady-state regime?*
- *How many analyses are necessary to achieve a complete characterization of the rig?*
- *How many analyses can be done by a group of four students during a single day of lab session?*
- *Are some parameters more relevant and/or more convenient to study than others?*
- *Do some operating conditions generate difficulties of operation for the pilot?*
- *Do we need to calibrate the measurement devices each day?*
- *How long do the students need to derive mass and energy balances?*

At the end of the day, the students have to give the teacher a planning sheet compiling the details (operating conditions) of the experiments they want their classmates (of the other groups) to perform. Special attention must be paid to the coherence of the operating conditions so that each group may carry out a complete study of the influence of at least one operational parameter. In particular, each group must collect a set of experiments that can be interpreted and that also contain at least one or two experiments dedicated to the repeatability and redundancy of measurements.

For example, concerning the liquid-liquid extraction laboratory, the flow rates of the feed and of solvent, as well as the pulsing frequency and amplitude, can be varied. For each set of operational conditions, students have to determine, at least, the composition of the currents (using chromatography or refractometry), the global and specific mass balances, and the number of theoretical stages using a triangular diagram. At the end of the day, the planning sheet established by the leading group must gather the operating conditions that will be tested by the other groups. This sheet must be presented using a clear and precise table that can be easily understood by the teachers and the other students.

Day 2

During the second day, students discover a new pilot-unit and have three main tasks:

1) Perform the experiments requested by the leading group of the unit on which they are working.

2) Write a report (called a basic report) concerning the results of the experiments and the analysis of the data. This report is given at the end of the day to the pilot-unit leading group of this unit.

3) Manage the group of students working on the apparatus they are in charge of. This last task includes the presentation of the apparatus, the explanation of the experimental schedule, and the management of their classmates all day long. Note that depending on the results obtained by each group, the planning sheet—which gathers the operating conditions—can be updated by the leading group at the end of each day, according to the notion of continuous quality improvement (for the so-called "Kaizen" attitude, described by Imaï and Kaizen[14]).

End of the session

One week after the last day of laboratory class, each group has to give a comprehensive report (called a pilot-unit leading group report) concerning the pilot apparatus they had to manage. This work is also evaluated by means of an oral presentation (about 20 minutes). This presentation must recall the principal parts of the report. The assessment tools will be described in part 4 of this paper.

Observed Evolution of Students' Behavior

The detailed objective of the pilot-unit leading group technique is to lead to the improvement of:

- Competencies related to investigation and analysis, as the students are expected to :
  - *conduct a literature search to collect information concerning the unit operation*
  - *design appropriate experiment schedules,*
  - *design and conduct analytical, modeling, and experimental investigations*
  - *interpret their own data and the data of other groups, and then draw conclusions*
- Competencies related to management and transferable skills. Indeed, all along the laboratory course, students experiment on how to manage a project, which makes them sensitive to their future professional experience. This is an active learning process and a real-time life experience: They have to act as an individual and as a member of a team structure; they have to share responsibilities, assign

roles among the group, define milestones and deadlines, monitor progress, and integrate the individual contributions of each group into a final deliverable (written report and oral presentation).

In addition, the pilot-unit leading group experience also delivers a strong message on aspects related to health, safety, security, and professional ethics, thus providing learning opportunities to develop specific competencies in these important skills.

The feedback of teachers who have experienced this approach, which has been applied at INPT-ENSIACET for several years, reveals different kinds of benefits for the students:

- *"During the laboratory class, students seem to be more concerned by the experiments they have to perform because their results have to be used by their classmates. For example, when there is a doubt concerning the protocol they directly refer to the 'pilot-unit leading group.' They do not hesitate to repeat an experiment that was not reliable enough. If they deviate from the given protocol, they derive in their report a discussion about the observed discrepancies."*
- *"The involvement of the leading group is excellent. They really take care of their apparatus and seriously consider the management of the other groups."*
- *"Students learn how to design and to estimate the quantity of work that can be done by their colleagues in a one-day period."*
- *"Students also experience how to delegate work to their classmates and how to manage technical staff (management of time, confidence in the results, etc.)."*

TEACHING-STAFF INVOLVEMENT/ COMMITMENT

The implementation of the pilot-unit leading group concept in the chemical engineering syllabus at INP-ENSIACET has modified some aspects of the pedagogy.

The teaching staff still has the responsibility of:

- *safety and security aspects*
- *the time schedule of the students (planning of turnover)*
- *evaluation of the relevance of operating conditions proposed by the pilot-unit leading group,*
- *evaluation of the relevance of methodologies available to address the objectives,*
- *evaluation of the assimilation of concepts learned in class.*

Some new aspects have to be taken into account, however. As pointed out by Lickl,[15] the teacher's role is not to be the "sage on the stage" but the "guide on the side." On day one of the pilot-unit leading group laboratory, the teacher's role is somewhat traditional: he/she gives explanations of the apparatus, of the relevant parameters to study, of how to run the analyses, etc. During the following days, the teacher's major role is to observe (especially concerning the security and safety aspects). The teacher must accept that the knowledge has to be delivered to a student by another student, rather than by himself/herself). The teacher must still make sure, however, that all technical aspects and fundamental theories are well transmitted, understood, and applied. As a result, the teacher is involved in discussions with the groups all day long.

A real effort has to be made by the teacher concerning possible misconceptions, which have to be checked more or less in real time. For instance, as mentioned before, the leading group can modify, at the end of each day, the planning sheet of the operating conditions in relation to the results obtained by the working group. This can only be done after a discussion with the teacher and under the teacher's agreement. Thus, this kind of pedagogy needs a high reactivity from the teacher, but the high motivation of the students is worth it!

ASSESSMENT TOOLS

Assessment of competencies acquired by the students

As previously mentioned, assessment of students' performances during pilot-scale laboratories covers several levels of skills and know-how, since the students have to produce different types of reporting during the entire laboratory instruction.

Students have to produce a basic report after each pilot-scale investigation—that means at the end of each day. Guidelines for this document are supplied to the students through a lab protocol, in which practical investigations and confrontation of their results with theoretical phenomena are demanded. The students are asked to give this report back to the teaching staff and to give a copy to the group of students (pilot-unit leading group) that is managing the apparatus they worked on. From an evaluation point of view, the objective of this basic report is to check that students have been able to perform the experiments, to observe the main physical phenomena involved, and to make a proper use of their results.

As said in the second part of this paper, at the end of the laboratories each student group also has to produce a typewritten report (referred to as the pilot-unit leading report), that contains a broad and complete analysis of the pilot-scale experiments for which they are the leading group. This report must contain several parts: a list of the industrial applications of the considered unit operation and the associated research fields, a description of the pilot-scale apparatus, the gathered experimental results of all groups, a critical and detailed analysis of the experimental results, a modeling study concerning at least one phenomenon that takes place within the pilot, and a discussion of the possible improvements that could be made to the apparatus. For this report, supplementary time (one week) is given to the students so that they can compile and analyze all data. Mainly evaluated through this work are the students' management capacity and their ability to analyze the experimental results. The students are also expected to develop critical evaluation skills on "what" and "why"; they should even suggest modifications to the pilot and lab work that would make them more efficient.

Finally, at the end of the laboratory session, the students are required to give an oral presentation (20 minutes) of their pilot-unit leading group experience. This presentation is done in front of the whole class so that every student hears a complete overview of each pilot-scale lab, even those that they have not managed. This oral presentation aims to check the students' clarity of expression and understanding, ability of technical presentations, and capacity to make a synthesis. The final mark awarded is a weighted average of the three assessments.

Details of the assessment tools are listed below:

Basic report: The evaluation of the basic report is based on specific studies that must be investigated by the students. As an example, the evaluation of students' performance for the liquid-liquid extraction laboratory is carried out using the criteria in Table 1, which has been established in connection with the guidelines supplied by the protocol.

The last topic of the assessment for the basic report leads to individual marks for the same experiment within a student group. This individual assessment can be a way of rewarding the conscientious students and of penalizing those who are less active.

Pilot-unit leading report: The assessment of the pilot-unit leading report is built on a different basis than the basic report. For the pilot-unit leading report, the degree of freedom left to the students is more important, since they have to prove their ability to gather, select, analyze, and synthesize experimental data, and this is largely dependant on their capacity to manage other groups on the pilot-scale unit they are leading. As said before, they are also encouraged to suggest in this report some modifications to improve the pilot or the pedagogical method. The criteria assessed in the pilot unit leading report are presented in Table 2. The evaluation of this report leads to a global mark for the whole group.

Oral presentation: An individual mark for each student is given from the oral presentation. During the oral presentation, students are evaluated on the criteria listed in Table 3 rather than on their technical skills and theoretical know-how that has been attained through the basic and the pilot-unit leading reports. Through the global assessment of each student during

TABLE 1
Evaluation Criteria for Basic Reports

General area	Details	Marks
Analysis of experimental results	Concentrations profiles	/4
	Steady-state achievement	
	Global residence time evaluation	/2
	Global mass balance	/2
	Solute mass balance	/2
	Saturation curve plotting	/1
	Minimum and maximum flow rates	/2
	Minimum flow rate for a specified separation	/2
	Number of theoretical plates	/2
	Evaluation of performance of separation (recovery rate, selectivity, efficiency)	/4
ProSim Plus® Software use	Simulation of extraction column	/5
	Comparison experiments/simulation	/4
Uncertainties analysis	Measurements uncertainties	/2
	Flow rates consistency	/2
Influence of operating conditions	Influence of operating conditions	/2
	Theoretical evaluation	/3
	General comments	/3
Conclusions	Over-design	/2
	Improvement proposals	/2
Practical assessment	Structure	/3
	Visual presentation	/3
Global behavior	Respect of safety instructions	/4
	Motivation/Involvement	/4
Total		/60

TABLE 2 Evaluation Criteria for the Pilot-Unit Leading Report		
General area	**Details**	**Marks**
General presentation	Structure	/5
	Clarity	
	Language/spelling mistakes	
Introduction/ Position of the problem	Presentation of the experiment	/5
	Identification of main physico-chemical phenomena	
	Literature study (industrial applications, technological improvements, safety recommendations, ...)	
Management of experimental investigations	Identification of relevant operating parameters	/10
	Distribution of experimental tasks to other group of students	
	Number of gathered experiments	
	Processing of gathered experimental results	
Analysis of experimental results	Repeatability of results	/10
	Uncertainties of measurements	
	Phenomenological analysis	
	Influence of operating conditions	
	Critical analysis	
	Comparison with theoretical calculations	
Critical evaluation	Pilot-scale performances evaluation (if possible)	/5
	Operability limits	
	Simulation (if possible)	
	Safety analysis (APR, HAZOP, if possible)	
General conclusions	Technical problems encountered	/5
	Suggested improvements	
Total		/40

TABLE 3 Evaluation Criteria for the Oral Presentation	
	Marks
Dynamism/personal implication	/4
Clarity of expression	/4
Precision of information	/4
Proper use of visual tools	/4
Ability to answer questions	/4
Total	/20

these pilot-scale laboratories, the 13 objectives defined in the previous section and listed by Feisel and Rosa[1] are finally intended to be explored.

Assessment of the instructional laboratories as seen by the students

At INP-ENSIACET, every teaching course is subjected to a final global evaluation made by the students. Students are free to respond to the survey or not; the response rate is generally greater than 90%. The objective is to obtain the students' perception of the course, to highlight any shortcomings, and thus to improve instructional and/or practical aspects. In the special case of these pilot-scale laboratories, the students were asked to respond to the questions presented in Table 4 (next page).

The six pilot-scale operations chosen for this new kind of teaching had been carefully selected for their ability to be adapted to the pilot-unit leading group concept; no influence of the type of unit operation that had to be lead during the session had been highlighted on the survey results.

As can be seen in the survey report, the application of the pilot-unit leading group approach has met rather enthusiastic reactions from students.

CONCLUSION

The development and assessment of competencies in engineering education require some innovative approaches to teaching. Through the implementation of the pilot-unit leading group approach, the chemical engineering students at INP-ENSIACET are provided with active learning activities and opportunities. It is through these activities and opportunities that several of the expected outcomes and transferable skills of the EUR-ACE[16] Framework Standards—*e.g.*, Knowledge and Understanding, Engineering Analysis, Engineering

Design, Investigations, Engineering Practice, Transferable Skills—are developed, demonstrated, and assessed. In addition, the 13 objectives for laboratory work as listed by Feisel and Rosa[1] are entirely accomplished within the learning environment.

ACKNOWLEDGMENT

The authors would like to thank the technical staff of the AIGEP platform for their valuable help during the laboratories.

REFERENCES

1. Feisel, L.D., and A.J. Rosa, "The Role of the Laboratory in Undergraduate Engineering Education," *J. Eng. Educ.*, **94,** 121 (2005)
2. McCreary, C.L., M.F. Golde, and R. Koeske, "Peer Instruction in the General Chemistry Laboratory: Assessment of Student Learning," *J. Chem. Educ.*, **83**, 804 (2006)
3. Young, B.R., H.W. Yarranton, C. Bellehumeur, and W.Y. Svrcek, "An Experimental Design Approach to Chemical Engineering Unit Operations Laboratories, Education for Chemical Engineers," *Transactions of the IChemE Part D* (2006)
4. Domin, D.S., "A Review of Laboratory Instruction Styles," *J. Chem. Eng.*, **74**, 543 (1999)
5. Birol, G., I. Birol, and A. Çinar, "Student Performance Enhancement by Cross-Course Project Assignments: A Case Study in Bioengineering and Process Modeling," *Chem. Eng. Ed.*, **35**, 128 (2001)
6. Jimenez, L., J. Font, J. Bonet, and X. Farriol, "To the Global Chemical Engineer Through the Holistic Unit Operations Laboratory," *Chem. Eng. Ed.*, **36**, 150 (2002)
7. Doskocil, E.J., "Incorporation of Experimental Design in the Unit Operations Laboratory," *Chem. Eng. Ed.*, **36**, 196 (2003)
8. Felder, R.M., and R. Brent, "Random Thoughts: Learning by Doing," *Chem. Eng. Ed.*, **37**, 282 (2003)
9. Newell, J.A., "Survivor: A Method for Active Learning in the Classroom that Addresses Student Motivation," *Chem. Eng. Ed.*, **39**, 228 (2005)
10. Jones, D., "Team Learning Approach in Education," *J. Quality and Participation*, **19**(1), 80 (1996)
11. Smith, K., "Cooperative Learning: Making 'Groupwork' Work Using Active Learning," *New Directions for Teaching and Learning*, **67**, 71 (1996)
12. Johnson, D., and R. Johnson, *Learning Together and Alone*, Allyn and Bacon, Boston, USA (1999)
13. Box, V.J., P.R. Munroe, A.C. Crosky, M.J. Hoffman, P. Kraulis, and R.A.J. Ford, "Increasing Student Involvement in Materials Engineering Service Subjects for Mechanical Engineers," *Int. J. Eng. Educ.*, **17**, 529 (2001)
14. Imaï, M., and G. Kaizen, "L'art de manager avec bon sens," *Editions JV&DS* (1997)
15. Lickl, L., "Work in Progress—Putting Engineering Pedagogy in Europe and Asia on an International Level," *37th ASEE/IEEE Frontiers in Education Conference*, Milwaukee, WI (2007)
16. EUR-ACE Framework Standards for the Accreditation of Engineering Programmes (2005), <http://www.feani.org/EUR_ACE/PrivateSection/Documents/A1_EUR-ACE_Framework%20Standards_2005-11-17corrected.pdf> ❐

TABLE 4
Survey Results

	Disagree (%)	Somewhat Disagree (%)	Agree (%)	Strongly agree (%)
Are the objectives of each laboratory clearly defined?	0	18.2	78.8	3.0
Does the global time schedule of the laboratories match the objectives?	0	3	66.7	30.3
Is the evaluation mode clearly defined at the beginning of the laboratories?	6.1	24.2	48.5	21.2
Is the technical organization suitable?	0	2.9	64.7	32.4
Is the equipment quality sufficient?	3.2	12.9	67.7	16.1
Is the equipment quantity sufficient?	0	0	58.8	41.2
Are the supplied documents relevant?	0	0	54.5	45.5
Are the teacher's explanations sufficient?	0	6.1	60.6	33.3
Do the teachers take enough time to answer questions?	0	6.1	36.4	57.6
Do the teachers encourage your personal reasoning?	0	9.4	75.0	15.6
Are scientific or technical exchanges with the teachers enriching?	0	0	64.7	35.3
Do the laboratories give you a clear view of the domain area concerned?	5.7	17.1	51.4	25.7
Do the proposed investigations enhance your personal thinking?	2.9	2.9	54.3	40
Do the proposed investigations lead you to develop interesting know-how?	2.9	14.7	58.8	23.5
Is the assessment mode satisfying?	3.0	15.2	78.8	3.0
Did you enjoy these laboratories?	0	21.2	69.7	9.1