DEVELOPMENT OF CONTEMPORARY PROBLEM-BASED LEARNING PROJECTS

In Particle Technology

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Recently, there have been attempts by several prominent engineers to raise awareness of the need for curriculum renewal in chemical engineering.[1, 2] In this context, the University of Sydney redesigned its undergraduate curriculum in 2004 to be more relevant to the educational needs of tomorrow's engineers.[3] This process involved an examination of what was taught, how it was delivered, and how students learned this material. As a result, a significant proportion of the revised curriculum was based upon the principles of Problem-Based Learning (PBL), *i.e.*, learning driven by the solution of open-ended problems. The new curriculum was rolled out from the beginning of 2005 and has been well received by students, academics, and industry alike.

In chemical engineering, the application of PBL is neither novel nor particularly controversial.[4, 5] To our knowledge, however, there are no published examples of the application of PBL in particle science and technology. We estimate that >75% of all industrial processes involve the processing of particles of some description, *e.g.*, powders, solid particles in fluids, polymers (emulsions), and biological systems (cells), and therefore consider this a worrying deficiency.

The core concepts and applications of particle science and technology were historically taught in the second semester of the penultimate (*i.e.*, third) year at Sydney using a traditional teaching and learning approach, *i.e.*, lectures and associated short tutorials, with small assignments throughout the semester and a final, graded examination. This course made use of several excellent textbooks,[6-8] however there was little integration, either with other subjects in the same semester, or material taught in other years. While the timing has remained the same, the new structure developed at Sydney now has strong integration within and across the four years of the curriculum.

Particle science and technology is now taught in the same semester as chemical product design, process design, process economics, project management, risk assessment, decision making, and entrepreneurship. This material is delivered in three administratively separate, but practically linked courses, which cover the basic fundamentals, enabling technologies, and engineering practice,[3] in accordance with the design of Sydney's new curriculum. These courses are compulsory for all undergraduate chemical engineers and have a value of 6 credit points; the standard across the University of Sydney. The typical enrolment is around 50 students and the course was run for the first time in 2005. The structure and content for second-semester, third-year is summarized in Table 1.

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This papers concerns the chemical engineering practice course (CHNG3807 in Table 1), in which the goal is to integrate the concepts and enabling techniques learned in the other courses through a series of projects. In this paper we discuss some of the background leading to the development of this course, describe the teaching, learning, and assessment rationale, and then briefly present the two major projects offered to students in 2005 and 2006. Finally, we conclude with an assessment of student reaction to the course, in terms of content and delivery.

TEACHING AND LEARNING METHODOLOGY

Harris and Briscoe-Andrews[9] have previously reported on the development of an advanced (postgraduate) course in chemical engineering delivered using the PBL methodology. The application of PBL in the chemical engineering undergraduate syllabus has also received attention.[4,5] PBL is a generic, student-centered, contextualized approach to learning,[10] whose forms may include research, case studies, guided design, engineering design projects, and small self-directed learning groups.[4,5] Woods has reported that in PBL the majority of time is spent learning—by identifying what you need to know, finding out, teaching each other, and then applying your new knowledge.[4] Thus, the primary aim of the exercise is the learning, not the completion of the project. The project is simply the means to this end.[4] In our work, the PBL methodology was developed in conjunction with medical education specialists at the University of Nottingham in the United Kingdom[11]; PBL has previously been reported to enhance teaching and learning outcomes in medicine.[10] This approach emphasizes: i) independent student learning (both individually and in small groups); ii) rigorous project formulation, problem definition, and project work plans; iii) discursive sessions; and iv) regular submissions with timely feedback.

In CHNG3807 our aim was to introduce students to the types of problems the modern chemical engineer is asked to solve, and to use these to drive student learning in product design, particle science, and technology. The subject matter is contemporary and the projects integrate key concepts across the curriculum, in particular linking with CHNG3805 and CHNG3806 (Table 1), while drawing heavily on material learned in earlier years (particularly mass and energy balances, thermodynamics, physical chemistry, physics and mechanics, mathematics and numerical methods, and an ability to write coherent reports based on qualitative and quantitative information).

Typically three projects are used; the first on product design (usually a four-week study on the development of water treatment technologies for remote communities), the second a short (one-week) project on innovation and entrepreneurship and then finally a major (eight-week) project focusing on particle science and technology. Over the past four years we have developed two major projects that are offered in alternating years: i) the design of a zero-emission coal power

TABLE 1
Overview of the 2nd-Semester, 3rd-Year Syllabus in Chemical and Biomolecular Engineering at the University of Sydney

Course code and title	Syllabus	Summary of teaching and learning approach
CHNG3805, Chemical Product Design	Chemical product design Innovation and entrepreneurship Particle science (properties and characterization of particles, sampling and measuring particles, single particles falling in fluids, hindered settling, measuring and analyzing particle size distributions, drag coefficients and terminal velocity, particles in fluids calculations) Particle technology (cyclone design, particulate transport, pneumatic conveying, packed beds, fluidized beds, storage and flow of powders, hopper design, size change, i.e. reduction and enlargement, filtration, surface activity).	Lectures and tutorials, assignments and a midsemester examination. Course is competency based (*i.e.*, pass/fail) with a final barrier examination at the end of semester.
CHNG3806, Management of Industrial Systems	Process engineering economics (Economies of scale, Cost estimation methods, Economic forecasting, Economic evaluation of projects, plans and processes, Business risk and uncertainty, Depreciation and tax provision) Risk assessment (Loss and waste prevention, Occupational health and safety, Concepts of hazard analysis). Project management (PM approaches and tools, Multi-objective optimization and trade-off analysis, Supply chain and value chain management, Life cycle management).	Lectures and tutorials, assignments and a mid semester examination. Course is competency based (i.e. pass/fail) with a final barrier examination at the end of semester.
CHNG3807, Chemical Engineering Practice II (Products and Value Chains)	Incorporates aspects of all of the material from CHNG3805 and CHNG3806 (above) with material from the first and second years of the curriculum into open ended projects.	Graded, project based assessment, involving a mixture of individual and group work. No final examination.

station, and ii) the design of a large-scale carbon nanotube synthesis facility. These offerings were designed to address "issues of scale" in chemical engineering, from molecular to macro-systems levels.

Both major projects draw heavily on our research interests and expertise. This is advantageous for several reasons—*e.g.*, we can present cutting-edge material to students to keep them interested throughout their studies—but mainly because we have available to us a bank of skilled and knowledgeable tutors, who are intimately familiar with the material being studied through their own Ph.D. research. We have previously reported that this is also advantageous for monitoring instances where students, either advertently or inadvertently, are guilty of plagiarism. Because the course material (and underlying published reference material) is very well known to the teaching and learning staff, it is comparatively simple to identify cases where plagiarism has occurred.[9]

ASSESSMENT

In our experience, most students only learn when they have to. The structure of the revised curriculum at Sydney (where there are major projects every semester) helps students to put into practice the concepts they have learned and is, in our opinion, an effective extension of learning from theory and tutorials. Not only does it provide students with an opportunity to understand how these concepts are used but also broadly identifies for them how this knowledge relates to other parts of their degree, well before they undertake their capstone design course.

For each case, students were presented with a technologically complex, real-life situation with no single correct answer. Their challenge was to develop a solution that was technologically sound and cost-effective. Students were assessed on the quality of a series of written reports and presentations. There was no midsemester or final exam. Students were expected to work in teams to explore the underlying issues, but the reports contained both group and individual components for assessment (such that the total assessment for the course was 60% individual, 40% group). In addition, with each assessment item, students were required to complete a peer and self assessment, during which they quantitatively and qualitatively rated their own contribution and the contributions of their peers. We have previously reported that a satisfactory peer and self assessment includes the following sections[9]:

i) a short paragraph documenting what contribution(s) the student has made to the project,

ii) a mark (out of 100) for the students' technical achievements.

iii) a mark (out of 100) for each of the other students', non-technical contributions (e.g., *attendance at group meetings, overall preparedness, initiative, team spirit).*

iv) short paragraphs documenting the contributions of the other group members to the project.

v) a mark (out of 100) for the technical achievements of every other member of the group.

vi) a mark (out of 100) for the other, nontechnical contributions of every other member of the group.

vii) the students' signature and date at the bottom of the document.

The numerical scores from these assessments were then factored into the final project mark awarded to each student by adjusting their mark either up or down, according to their deviation from the mean group mark determined from the peer and self assessments. Historically, the maximum deviation in marks across a group has been 20%.

MAJOR PROJECTS IN PARTICLE TECHNOLOGY

To give an idea of the working process for each project, we present the two major case studies used in 2005 and 2006, on zero-emission coal electricity and the large-scale production of carbon nanotubes, respectively. Both cases were the major assessment item in their respective years, valued at 70% of the course mark.

Each project began with a (very broad) statement of the problem and was typically supported by a keynote lecture, learning topics, lists of keywords and references, lecture and workshop materials, experimental data, and Web sites of interest—although this material was not all made available initially; students had to specifically request it. The cases were real-world problems, *i.e.*, they were complex and open-ended, with incomplete data, and required rapid generation and rejection of solution alternatives. They were also framed within a real-world context, *i.e.*, they incorporated aspects of safety, economics, ethics, regulation, intellectual property, and market and social needs. Furthermore, both technical and nontechnical attributes were emphasized during the projects. This required students to develop and demonstrate technical knowledge as well as generic skills in research and enquiry, information literacy, personal and intellectual autonomy, communication, and ethical, social, and professional understanding, consistent with the teaching and learning aims of the University of Sydney.

Zero-Emission Coal

This project began with an introductory lecture on energy supply and demand and the available technologies to meet this demand into the future. Australia has a cheap, plentiful supply of coal sufficient to last hundreds of years, even considering future demand. Thus, the coal industry plays a major role in Australia, both economically and as an employer of engineers. Coal is an unsustainable resource, however, which when burned, contributes to the problem of global warming through enhanced emissions of CO_2. One of the options being examined, in Australia and elsewhere, is to develop "zero-emission" coal processes. In essence this involves the capture and sequestration of the CO_2 emissions. Following this lecture and background information students were given the following brief:

> *"You are a design engineer working as part of the lead design team for a firm of consulting engineers. Your client, a large Australian mining and energy company, has commissioned your firm to design a 'next generation' coal-fired power plant. Your task is to prepare a preliminary design report for this process. The report should outline the new technology, compare it with other suitable approaches, and give supporting design calculations, where appropriate."*

For this project students were allowed to choose their own groups. We have used other strategies to form groups, including random assignment and seeding according to ability (so each group has a range of abilities). We have found no appreciable differences in performance across groups using any of these techniques, however—*i.e.*, individual students tend to achieve a mark consistent with their historical performance irrespective of the other group members—and so we have tended to use the simplest approach to forming groups. Once students had received the brief and formed into groups, the class ended for the day. In most years the teaching and learning staff are asked for the design basis (*i.e.*, how big is the plant) before this happens, but not always.

The next class, held two days later, was a three-hour workshop (as were all the remaining student-staff contact sessions for the project—there are two of these sessions timetabled each week) where students could begin to formulate the exact problem they had to solve. This process typically takes one week and involves extensive examination of the issues, suggestions and rejection of ideas, and discussion with the teaching and learning staff. Following this process, which occurs with individual groups, not the class as a whole, we agreed on a set of objectives for the project, as follows:

Prepare a preliminary design report for a zero-emission coal technology giving supporting design calculations for the i) fluidized bed gasifier, ii) feed storage and iii) handling system, iv) calcination reactor, v) gas clean-up, and vi) carbon sequestration reactor. Another company will design the fuel cell. The design basis is 500,000 tpa (dry basis, coal feed). A block diagram of the system is given in Figure 1. The preliminary design report should include: i) a description of the basic technology, how it works, the underpinning chemistry, and a literature review of possible alternate designs; ii) a process flow diagram (PFD) incorporating mass and energy balances

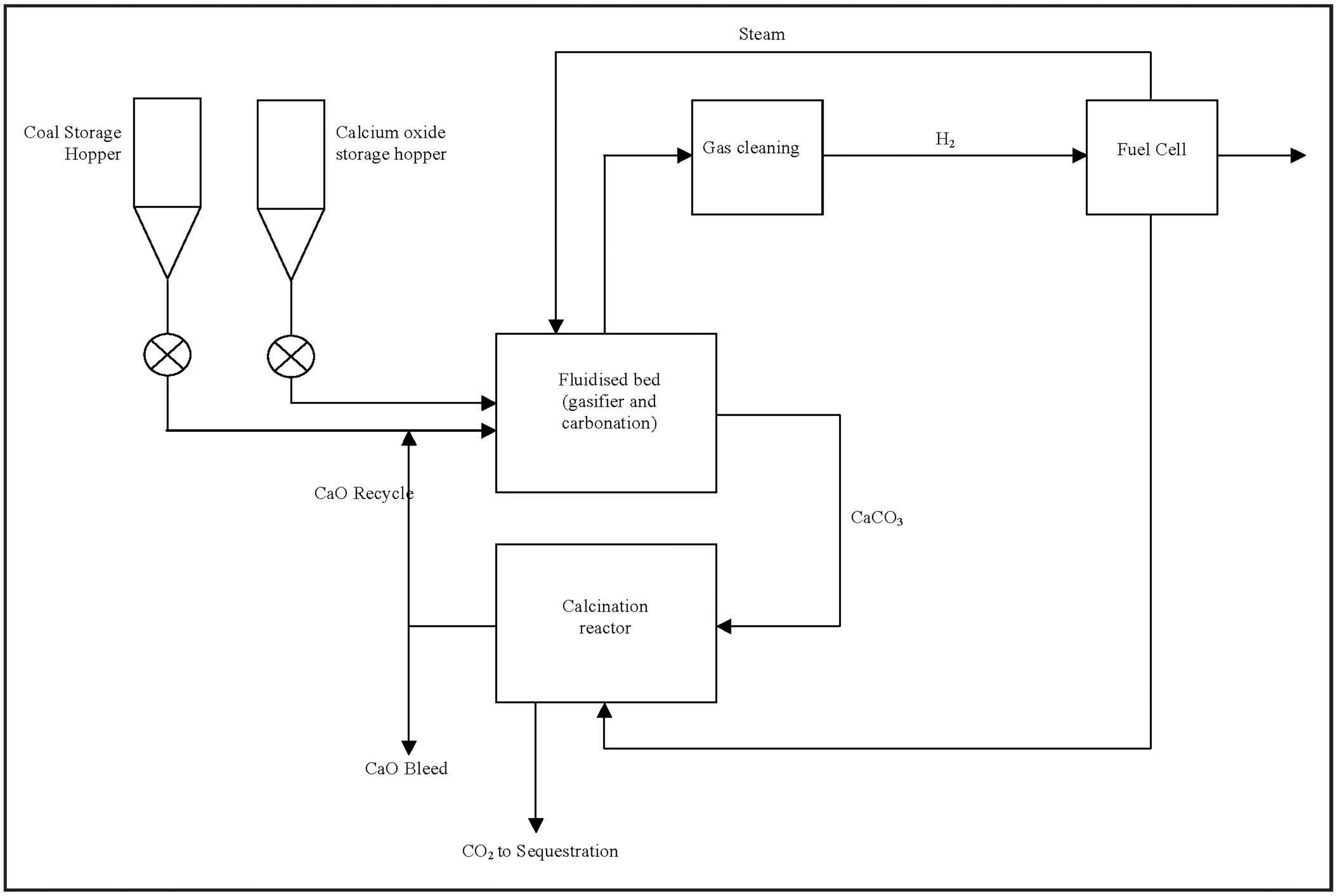

Figure 1. *Sketch of the zero-emission coal reactor and ancillaries.*

(but not a process and instrumentation diagram, P&ID); iii) order of magnitude (± 25%) sizing and performance calculations for each of the unit operations in Figure 1, *i.e.*, coal and calcium oxide storage and feed systems, hopper, rotary valve and pneumatic conveying system, pneumatic conveying system between the gasifier and the calcination reactor, fluidized bed gasification reactor, gas cleaning cyclones and electrostatic precipitator, carbon sequestration reactor (a high pressure slurry reactor); and iv) preliminary (±25%) capital and operating cost estimates for the plant.

Students were then also given the usual guidelines about the length of the report, its structure, appropriate referencing, and warnings about the consequences of plagiarism.

The design reports and accompanying presentations were generally of a high standard, reflecting the effort put into them.

Large-scale Carbon Nanotube Synthesis

Carbon nanotubes are a form of crystalline carbon with unique properties, which make them potentially valuable in a wide range of end-use applications. Currently, research into nanotubes and their applications is hampered by the lack of a suitable technique for manufacturing them in large quantities, which we have defined previously as being of the order of 10 000 tons per plant per year.[12] There are three established methods for CNT synthesis: (i) arc discharge, (ii) laser ablation, and (iii) chemical vapor deposition (CVD). Of these, CVD techniques show the greatest promise for economically viable, large-scale synthesis, based on yields reported in the literature and the inherent scalability of similar technologies, *e.g.*, fluidized catalytic cracking. In particular, the fluidized-bed CVD technique (where the CVD reaction occurs within a fluidized bed of catalyst particles) has the potential to produce high-quality CNTs, inexpensively, in large quantities.[12]

The structure and working process for this project was identical to that for the zero-emission coal study described above. To begin, students were given an introductory lecture on nanotechnology and carbon nanotubes, and then were issued with the following brief:

> *"You are a design engineer working for a start-up 'nanotech' company. Your company has acquired the IP (patents and other information) for a laboratory-scale (1 kg/day) fluidized-bed carbon nanotube synthesis process. Your first job for the company is to assist with the preliminary design for a commercial-scale (5000 kg/day) nanotube synthesis process using this technology. A sketch of our technology is attached (Figure 2)."*

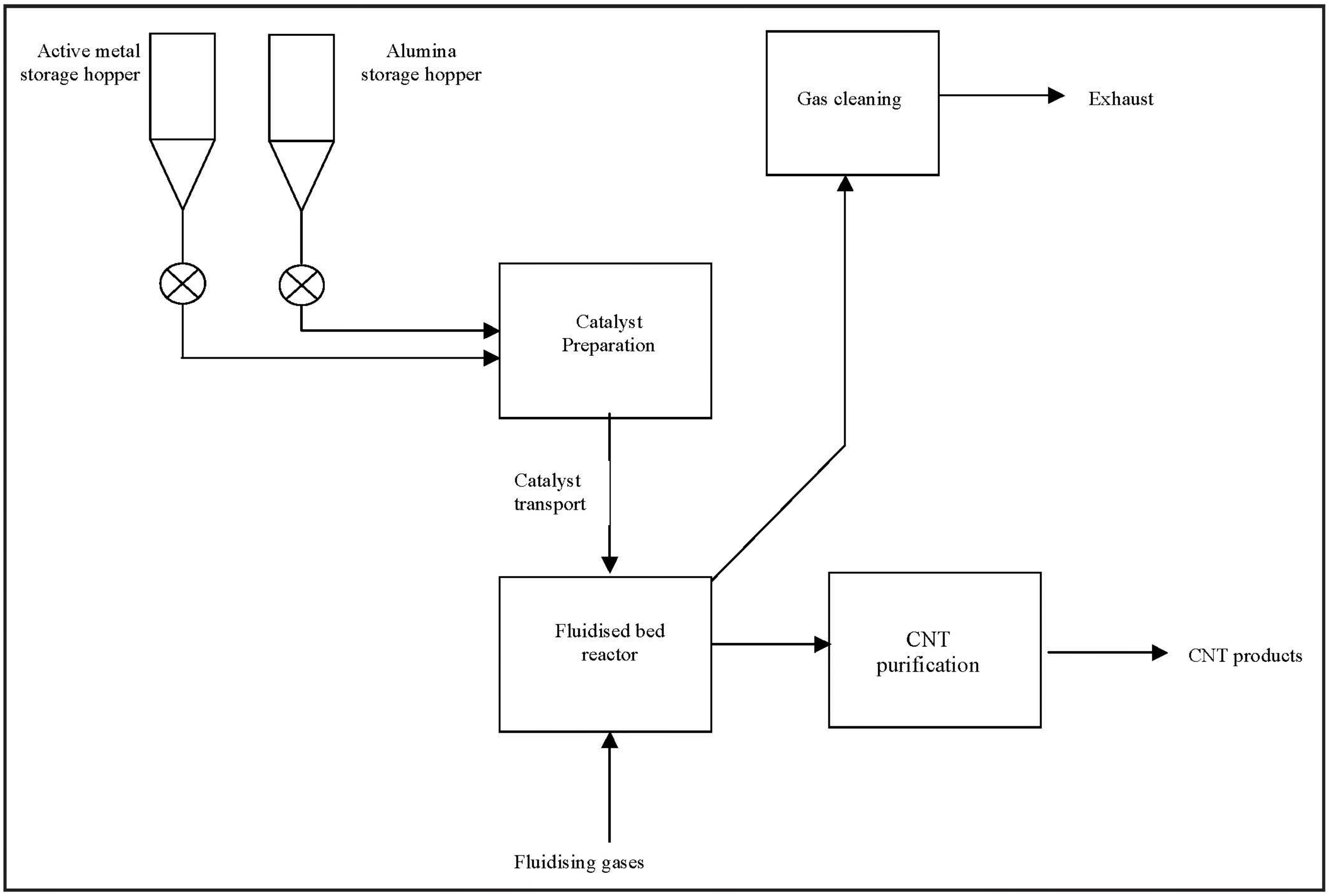

Figure 2. *Sketch of the carbon nanotube synthesis facility.*

After the usual process of rapid idea generation, rejection, and adaptation, the teaching and learning staff and students arrived at a mutually agreed project brief, as follows:

Prepare a preliminary design report for a carbon nanotube manufacturing facility that: i) outlines the technology, how it works, the underpinning chemistry, and possible alternate designs; ii) assesses its performance (including the production of a PFD with mass and energy balances), and gives supporting information (order of magnitude, ± 25% sizing and performance calculations) for the fluidized bed CVD reactor, catalyst preparation system (slurry reactor, drier ,and furnace), catalyst storage, handling and feed system (hoppers, rotary valve, and pneumatic conveying system), product purification system (slurry reactor and nano-filtration) and gas clean-up system (cyclones, electrostatic precipitator, and wet scrubber). Capital and operating costs (±25%) were also required.

Again, the design reports and presentations were of a comparatively high standard.

STUDENT FEEDBACK

Student feedback via the formal course evaluation (a confidential paper-based survey containing 12 questions, managed by the University's Teaching and Learning center) showed that in 2005 (the first time the course was run), overall student satisfaction with the course was below average, with only 21% of students agreeing or strongly agreeing with the statement "Overall I was satisfied with the quality of this unit of study," although this increased to 43% in 2006 (no data are available for 2007). This compares with 39% who disagreed or strongly disagreed with this statement (31% in 2006). These scores are partly attributable to several factors: i) a perceived high workload relative to their other classes (69% agreed or strongly agreed with the statement "The workload in this unit of study was too high" in 2005; 71% in 2006); ii) the fact this was the first time students had been substantially exposed to the PBL methodology in their studies (many students made individual comments that they would have preferred more lectures and tutorials and fewer project workshops); and iii) a perception that their prior learning had not adequately prepared them for this type of course (41% agreed or strongly agreed with this statement in 2005; 50% in 2006).

Students did report, however, that they were very satisfied with the way the course helped them develop valuable generic attributes, *e.g.*, research inquiry skills, communication skills, and intellectual autonomy (76% agreed or strongly agreed with the statement "This unit of study helped me develop valuable generic attributes" in 2005; 83% in 2006). They also indicated they could see the relevance of the course to their broader education (66% in 2005; 91% in 2006). We take this as an indication that students knew the course was good for them, they just didn't like it very much because it was difficult. We have continued to streamline and improve the course, in particular including an experimental component where students can gather yield and kinetic data for the production of carbon nanotubes, which they then use in their design calculations.

Our goal for students at the end of the course was that they should be proficient at:

- i) *developing a strategy for taking a product development idea from concept to commercial artifact, with a comprehensive appreciation of economic arguments, underlying uncertainties (and mitigation of these), and consideration of trade-offs inherent in this development – and demonstrating this in project mode;*
- ii) *applying design and analysis tools for the synthesis of particulate products leading to manufacture of a preferred product at pilot scale – and demonstrating this in project mode;*
- iii) *developing a strategy for design and analysis of extended business enterprises, with a focus on value chain optimization - and demonstrating this in project mode;*

And should have developed:

- iv) *improved research skills and an ability to cope with ambiguity;*
- v) *an ability to select appropriate engineering principles to solve open-ended problems;*
- vi) *engineering practice skills.*

We do not have an opportunity to include an assessment of these in the formal course evaluation, but operate our own (non-confidential) questionnaire with students at the completion of the course to help assess this. This survey contains most of the same questions as the formal evaluation (we use this as a sort of internal benchmark) and uses the same response format, but also includes questions on the specific teaching and learning objectives (iv, v and vi above). During this survey, a majority of students in both 2005 and 2006 indicated that they had improved their abilities in these areas. In 2005, 71% of students agreed or strongly agreed with the statement "The problem-based learning style helped me develop important skills and cope with ambiguity." In 2006 the number was 75%. In both years no student disagreed with this statement.

CONCLUSIONS

Knowledge of the processing behavior of particles is important for most practicing chemical engineers. To this end, the University of Sydney has developed an undergraduate course in particle science and technology using a problem-based learning methodology. Students found the course challenging, but rated highly the generic attributes the teaching and learning style helped them develop.

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