Results of the 2010 Survey on TEACHING CHEMICAL REACTION ENGINEERING

DAVID L. SILVERSTEIN
University of Kentucky • Paducah, KY 42002
MARGOT A.S. VIGEANT
Bucknell University • Lewisburg, PA 17837

The Chemical Reaction Engineering (CRE) course, while currently an essentially undisputed part of the core chemical engineering curriculum, is actually a fairly recent addition to the curriculum. A retrospective paper by Fogler and Cutlip[1] describes the introduction of the topic in the 1940s as one characterized by "gross approximations" for slide-rule calculations as part of broader process operations courses, while today it has developed into a dedicated, more computationally oriented course.

In 1957 the AIChE Education Projects committee began a series of surveys of the undergraduate curriculum as offered by chemical engineering departments in North America. These surveys continued under the auspices of the AIChE Special Projects committee until the late 1990s. In 2008, AIChE formed an Education Division which recognized the value of the survey for its characterization of how courses are taught at a broad range of institutions as well as for the opportunity to share innovative and effective teaching methods associated with specific courses. This paper presents the results for the second in the series of surveys conducted by the Education Division.

Much of the content of this paper was previously published as part of the American Society for Engineering Education 2011 conference proceedings.[2] This paper adds additional analysis and comparison with data from previous surveys.

SURVEY BACKGROUND

The Chemical Reaction Engineering course (CRE) is the topic of the 2010 survey. The aforementioned AIChE Education Projects committee previously conducted surveys on the same course in 1974,[3] 1984,[4] and 1991.[5] Other surveys on this course from that committee may exist but were not obtained by the authors. The current survey was designed in part to update the results published for those surveys.

The survey was conducted via Internet server hosted by the University of Kentucky running an open source software package, LimeSurvey (<*limesurvey.org*>). E-mail invitations to participate were initially sent to all department chairs in the United States and Canada requesting participation from the faculty members teaching the relevant course(s). A second

David L. Silverstein *is currently the PJC Engineering Associate Professor of Chemical and Materials Engineering at the University of Kentucky, College of Engineering Extended Campus Programs in Paducah. He received his B.S.Ch.E. from the University of Alabama in Tuscaloosa; his M.S. and Ph.D. in chemical engineering from Vanderbilt University in Nashville; and has been a registered P.E. since 2002. Silverstein is the 2004 and 2011 recipient of the William H. Corcoran Award for the most outstanding paper published in* Chemical Engineering Education *during the previous year, and the 2007 recipient of the Raymond W. Fahien Award for Outstanding Teaching Effectiveness and Educational Scholarship.*

Margot Vigeant *is an associate professor of chemical engineering at Bucknell University, where she has enjoyed working with students since 1999. She graduated with a B.S. in chemical engineering from Cornell University, and her M.S. and Ph.D. from The University of Virginia. With Mike Prince and Katharyn Nottis, she received the 2011 "best paper" award from the ASEE Educational Research and Methods Division and from PIC IV. Since 2009, Margot has also been moonlighting as an associate dean of engineering.*

request was sent to the instructors of record for the CRE course during the 2009-2010 academic year when that information was publicly available on the Internet. From that population of 158 programs, 62 usable surveys representing 60 institutions were received.

This 38% response rate represents an improvement from the results of the 2009 survey on the freshman introductory courses[6] (31%), but still falls short of the response rates in 1974 (58%) and 1984 (91%). No response data is available for the 1991 survey.

Responding programs represented great regional diversity and size, covering the United States and three Canadian provinces. Seventy percent of responding programs were from public institutions. The smallest responding department had an overall undergraduate chemical engineering enrollment of 37 students in 2010, while the largest had 730 undergraduates.[7] Median undergraduate program enrollment for responding institutions is 177.

The complete survey in print form is available in the ASEE Proceedings paper.[2]

COURSE TIMING

The most common timings for the course within a program's curriculum were at the end of the junior year or at the start of the senior year, with a slight edge to the junior-year start. The distribution of the timing of course offerings is given in Figure 1. Figure 2 offers a historical comparison of offerings by term, which indicates there has been a shift toward offering the first course in CRE to the junior year. In 1974, 13% of reporting programs taught the course in the junior year, and in 2010 that percentage is about 50%.

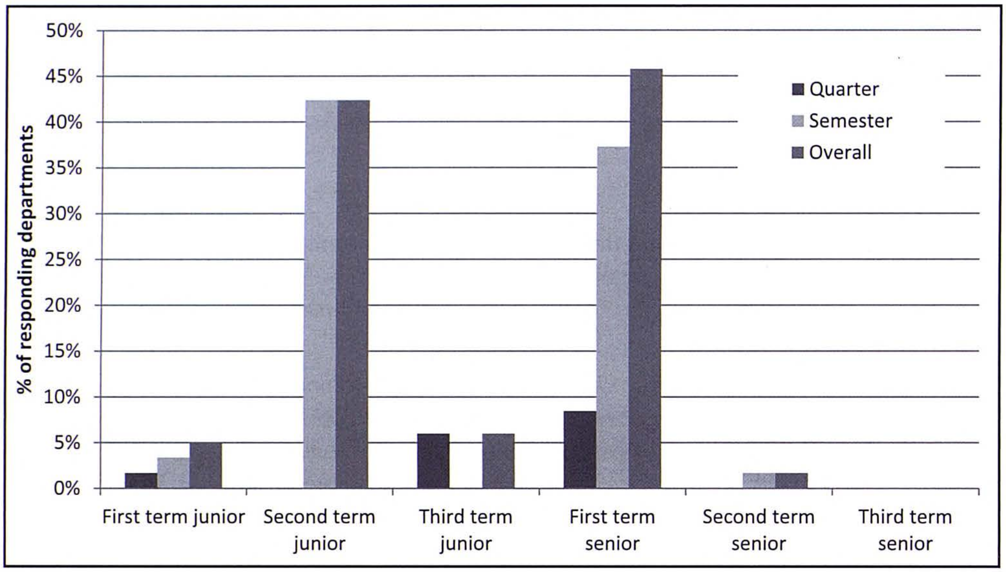

***Figure 1.** 2009-2010 offerings of CRE by term as reported by instructors.*

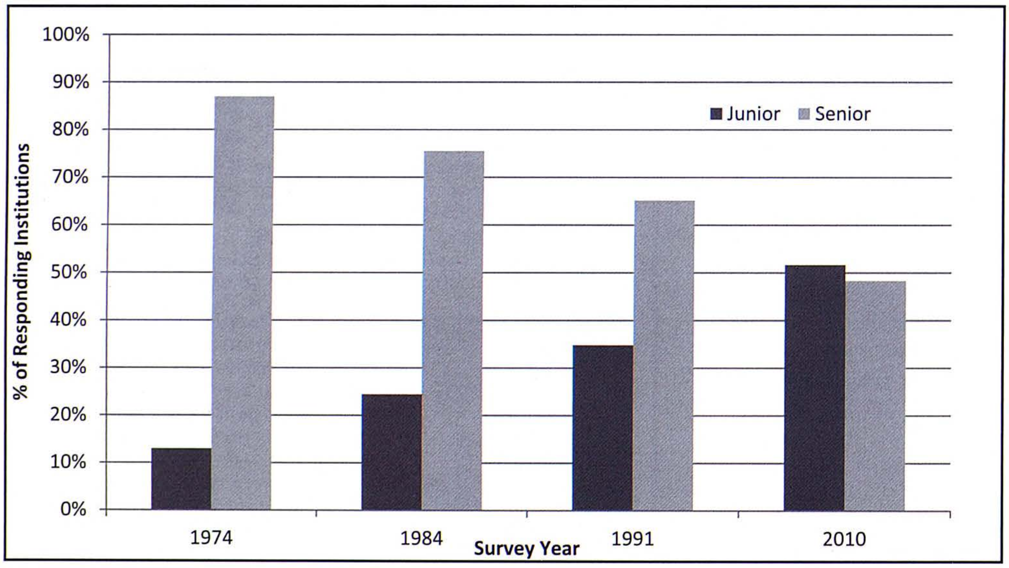

***Figure 2.** Timing of first offering of CRE course. Data for 2009-2010 as reported by instructors.*

QUANTITY OF INSTRUCTION

Of the 60 institutions reporting, 55 indicated they offered a single course in CRE. The remaining five offered two courses. Of those institutions, three were on the quarter system. Those 60 institutions reported 3.7 h/wk total devoted to the course, broken up into an average 2.9 h/wk on lecture, 0.6 h on problem solving, and 0.2 h/wk on experimental laboratory. Only five of the 55 offer experimental laboratories, ranging from 30 minutes to 3 hours weekly.

In 1971, 3.06 h/wk of lecture and problem laboratory were reported, with 0.40 h/wk in experimental laboratories. The "typical" undergraduate experience has never included a laboratory specifically for this course. In 1971, 30% of universities responding indicated experimental labs, with an average reported time of 1.5 h/wk. The 1984 report indicated 6% of courses included a 1-hour experimental lab and 4% had a 3-hour experimental laboratory. The 1991 survey indicated an average of 3.41 h/wk in lecture, with an average of 1.91 h/wk experimental laboratory among the 22% of departments offering a laboratory as part of the CRE course. Figure 3 shows the historical changes in laboratory exercises associated with CRE courses.

CLASS SIZE

The typical size of a class section does not appear to have changed significantly over the past several decades, as shown in Figure 4. Since the bin sizes varied for each survey analysis, it is not possible to compare between survey results directly. In 2009-10, the average class size was 40. This falls in between the 1984 average of 43 and the 1990-91 estimated average of about 33.

When comparing section enrollment data with Figure 3, it appears that as class sizes increase, the number of programs incorporating laboratory exercises into a traditionally lecture course seems to decrease.

Classes are primarily taught by professional instructors, with only eight programs (12.5%) reporting teaching assistants (TA's) delivering lectures. Among those programs, a maximum of 10% of lectures were given by TA's, with the average being 3.7%.

The prerequisite courses declared by instructors in 2010 are given in Figure 5. Note that

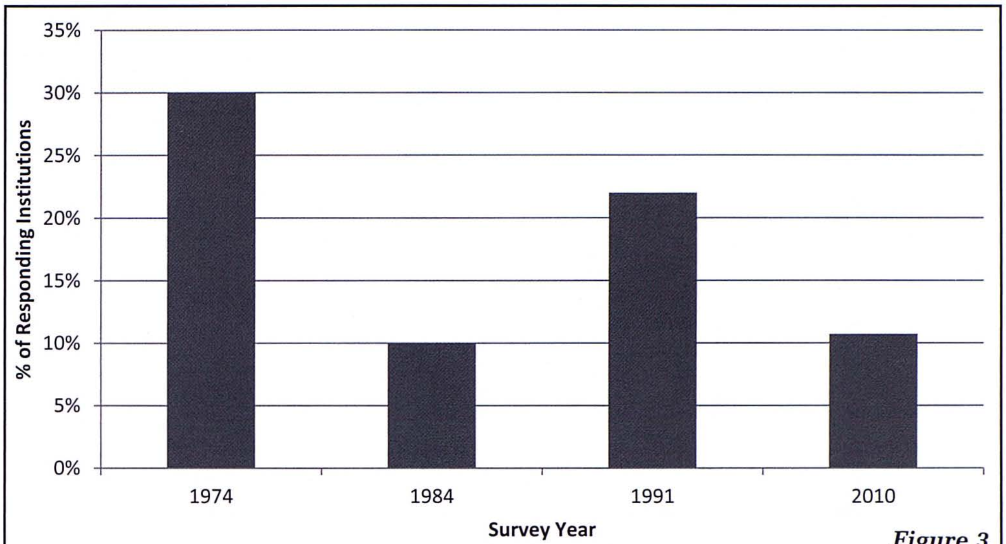

Figure 3

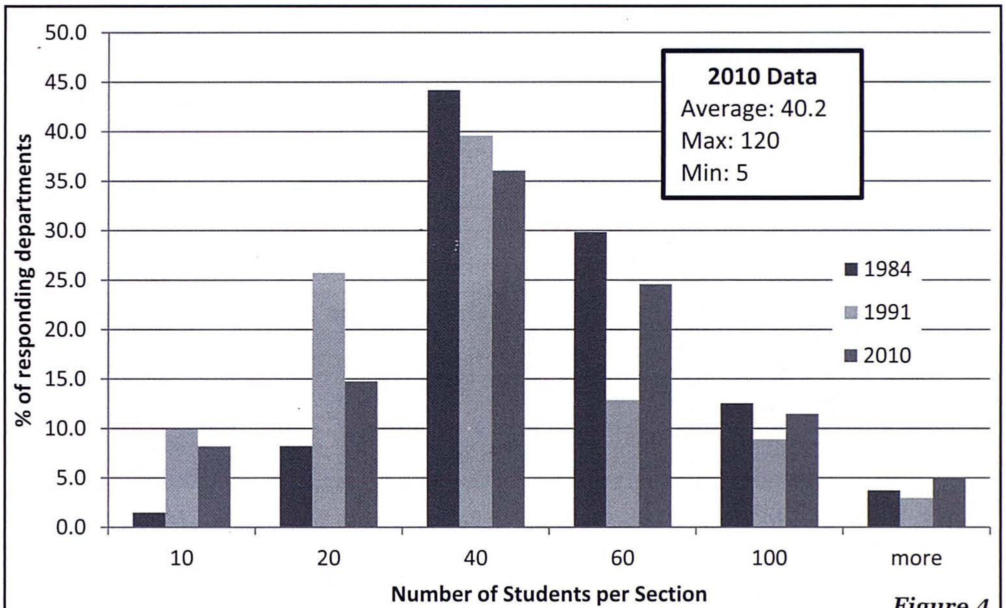

Figure 4

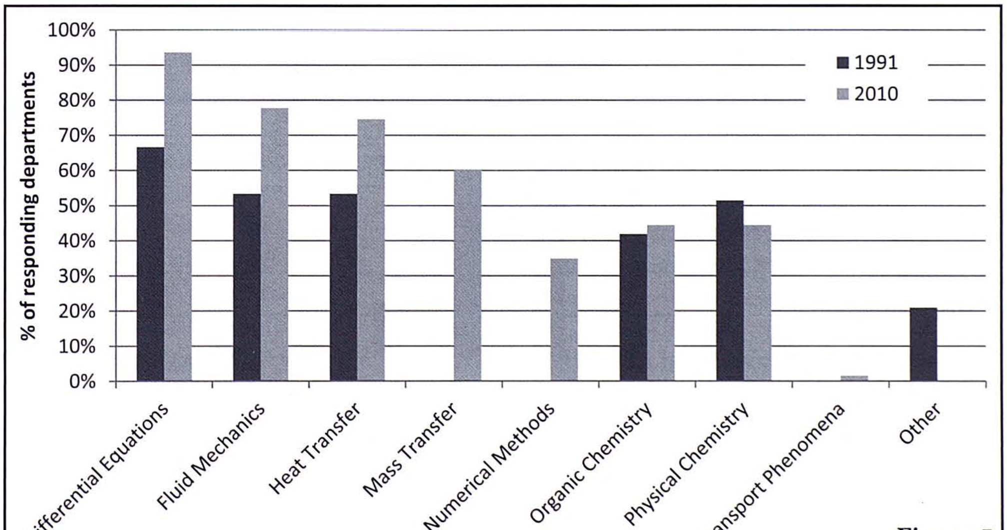

Figure 5

Figure 3 (top). *Percentage of responding programs offering laboratory exercises in conjunction with the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 4 (middle). *Section size for the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 5 (bottom). *Prerequisite courses (formal and informal) reported by instructors.*

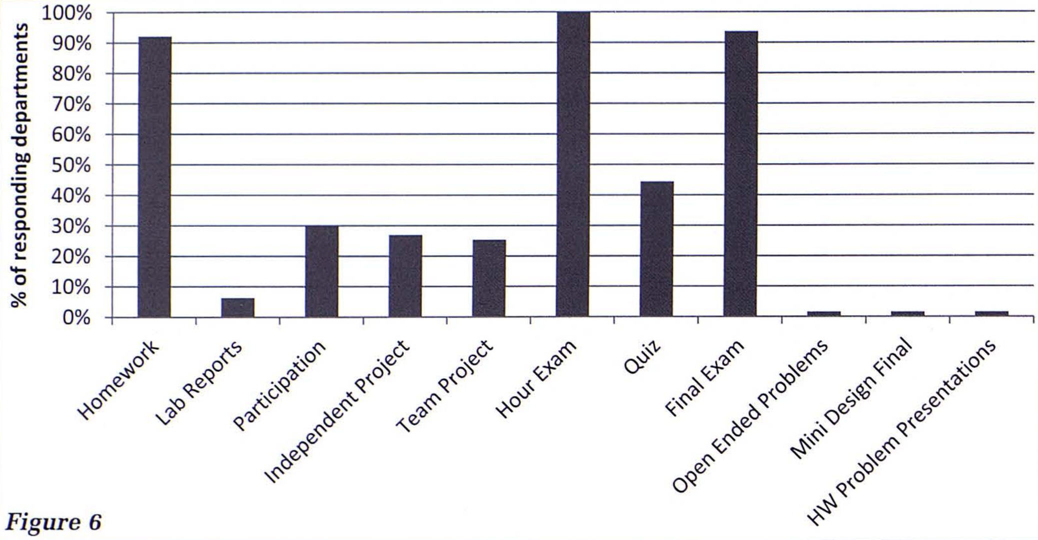

Figure 6

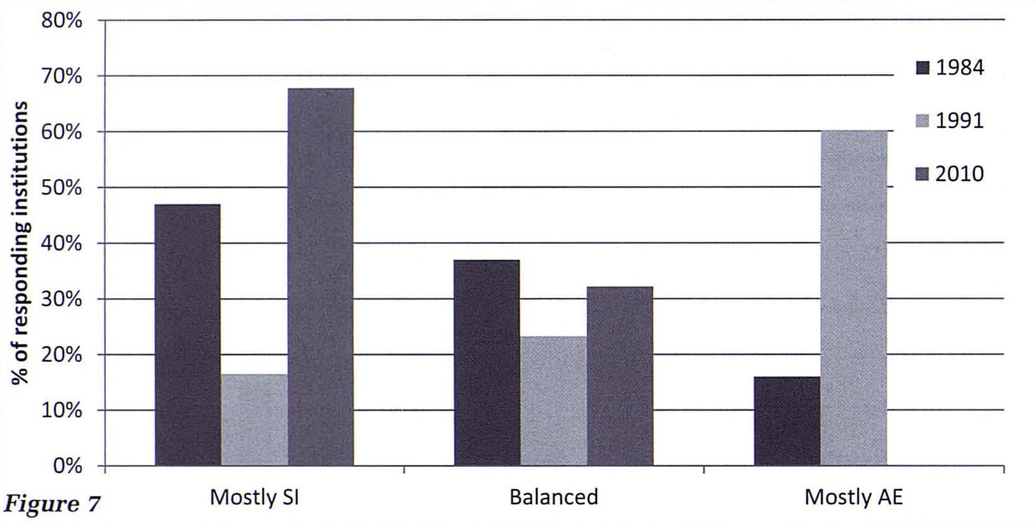

Figure 7

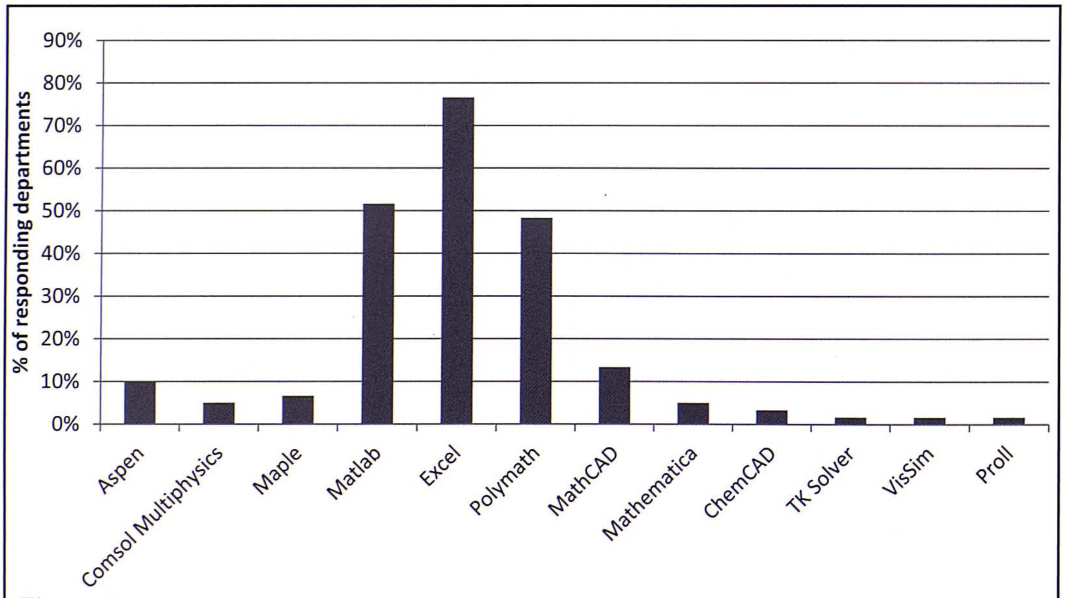

Figure 8

transport-related courses have increased in frequency of requirement. Some programs simplify the prerequisite list by requiring "junior-" or "senior-standing," and do not give this full list of requirements explicitly in their course catalogs.

A wide range of student deliverables was required, as shown in Figure 6. When likely "open-ended" problems (independent and team projects, open-ended problems) are combined, about 54% of courses require open-ended design work. In the 1991 survey, 93% of departments indicated they would occasionally or often use open-ended design problems if they were available in their textbook. In that 1991 survey, 33% of departments indicated a project assignment.

The primary unit system used in CRE problems has also changed over time. Figure 7 shows how there appears to be a transition from a push to SI in 1984 followed by a return to American Engineering (AE) units in 1991 to a more balanced but leaning SI approach today.

Figure 6 (top). *Deliverables required for the course in 2009-2010 as reported by instructors.*

Figure 7 (middle). *Characterization of unit systems used in problems encountered in the CRE course. Data for 2009-2010 as reported by instructors.*

Figure 8 (bottom). *Software used in the CRE course in 2009-2010 as reported by instructors.*

Software usage by programs was varied, as shown in Figure 8. Perhaps most notable is the lack of industrial process simulation combined with the emergence of finite element modeling. In 1991, the most common language/program reported was FORTRAN (71 programs) followed by Lotus (presumably the 1-2-3 spreadsheet), Basic, Pascal, and Flowtran.

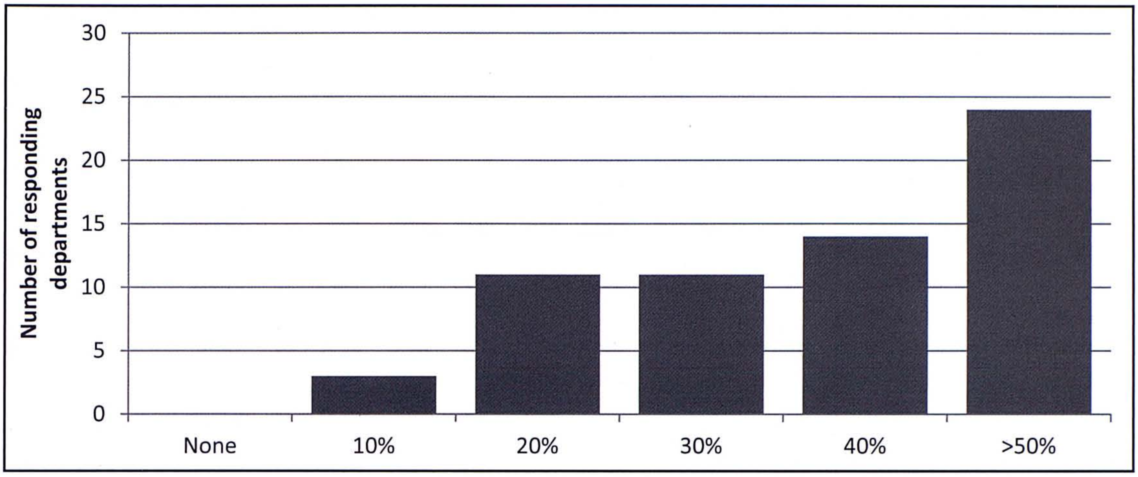

Figure 9. *Percent of homework assignments requiring use of computer software in 2009-2010 as reported by instructors.*

The use of computer software in routine homework assignments is significant as shown in Figure 9. Other use of computers in the course includes use of course management software (CMS such as Blackboard) or web pages primarily for making available class notes and homework solutions. Some utilize Internet-based references for thermodynamic and transport properties, or to collect real-world operational data. Other schools provide exams from previous years for students to study, providing a "level playing field" for those without access to collections of old exams. Video from television programs like *MythBusters* is used for safety discussions. Animations collected from FEM/CFD software are used. Online reactor labs such as <*www.SimzLab.com*> enhance the course. Online texts are also used by some, such as Carl Lund's KaRE TExT, <*http://www.eng.buffalo.edu/Research/karetext/front_matter/title/info.shtml*>. The Chemical Safety Board also has relevant videos available online. Some textbooks offer significant supplementary material, including tutorial software, on their associated websites.

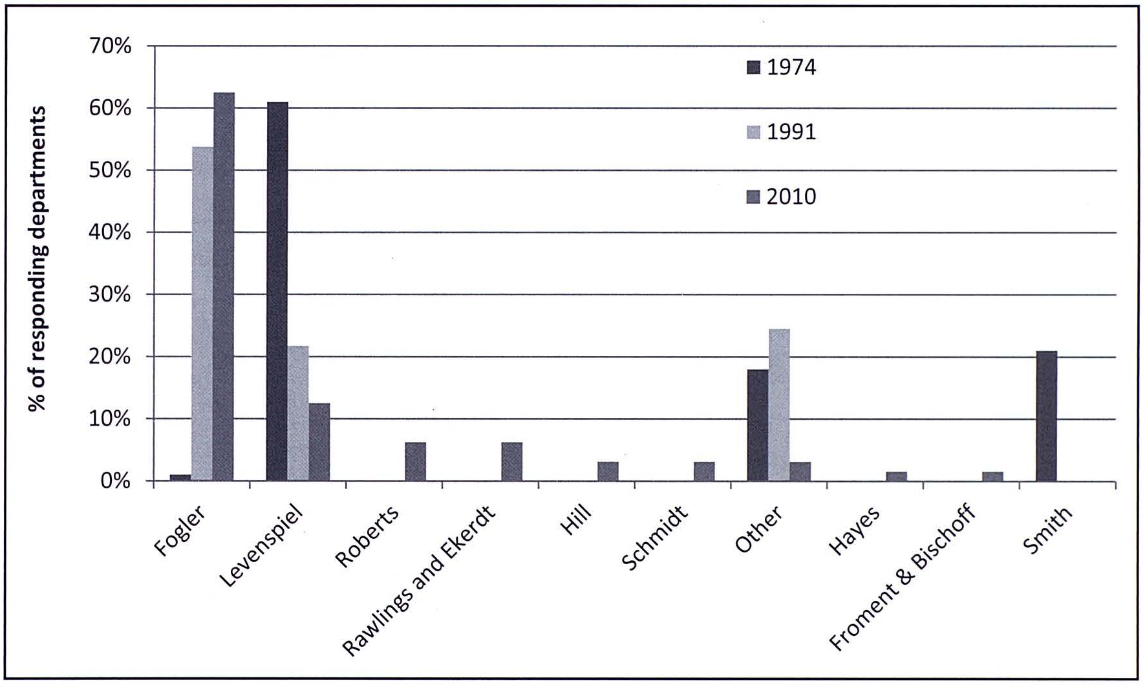

Figure 10. *Adoption of textbooks. For a particular lead author, multiple editions may be represented. Data for 2009-2010 as reported by instructors.*

Textbooks reported as currently in use include:

- *Fogler,* Elements of Chemical Reaction Engineering, *4th Ed.*
- *Levenspiel,* Chemical Reaction Engineering, *3rd Ed.*
- *Roberts,* Chemical Reactions and Chemical Reactors
- *Rawlings & Ekerdt,* Chemical Reactor Analysis and Design Fundamentals
- *Hill,* An Introduction to Chemical Engineering Kinetics and Reactor Design
- *Schmidt,* The Engineering of Chemical Reactions
- *Froment and Bischoff,* Chemical Reactor Analysis and Design

Figure 10 illustrates the rise and fall in popularity of CRE textbooks over the past 36 years.

The changes in course topics are reflected in changes in textbook coverage and the use of those chapters. Figure 11 shows the usage of particular chapters in Fogler's textbook in both 1991 and 2010 among those institutions reporting adoption of the text.

There is general satisfaction with existing texts on the subject, though some would like to see a more concise textbook containing one semester's coverage. Some express an interest in additional coverage of safety topics and bioreactors, although as shown in Figure 11 the reported usage of a chapter on bioreactors has actually decreased since 1991. Some cite weak areas in specific textbooks in coverage of mixing, reaction kinetics, and non-isothermal reactor design.

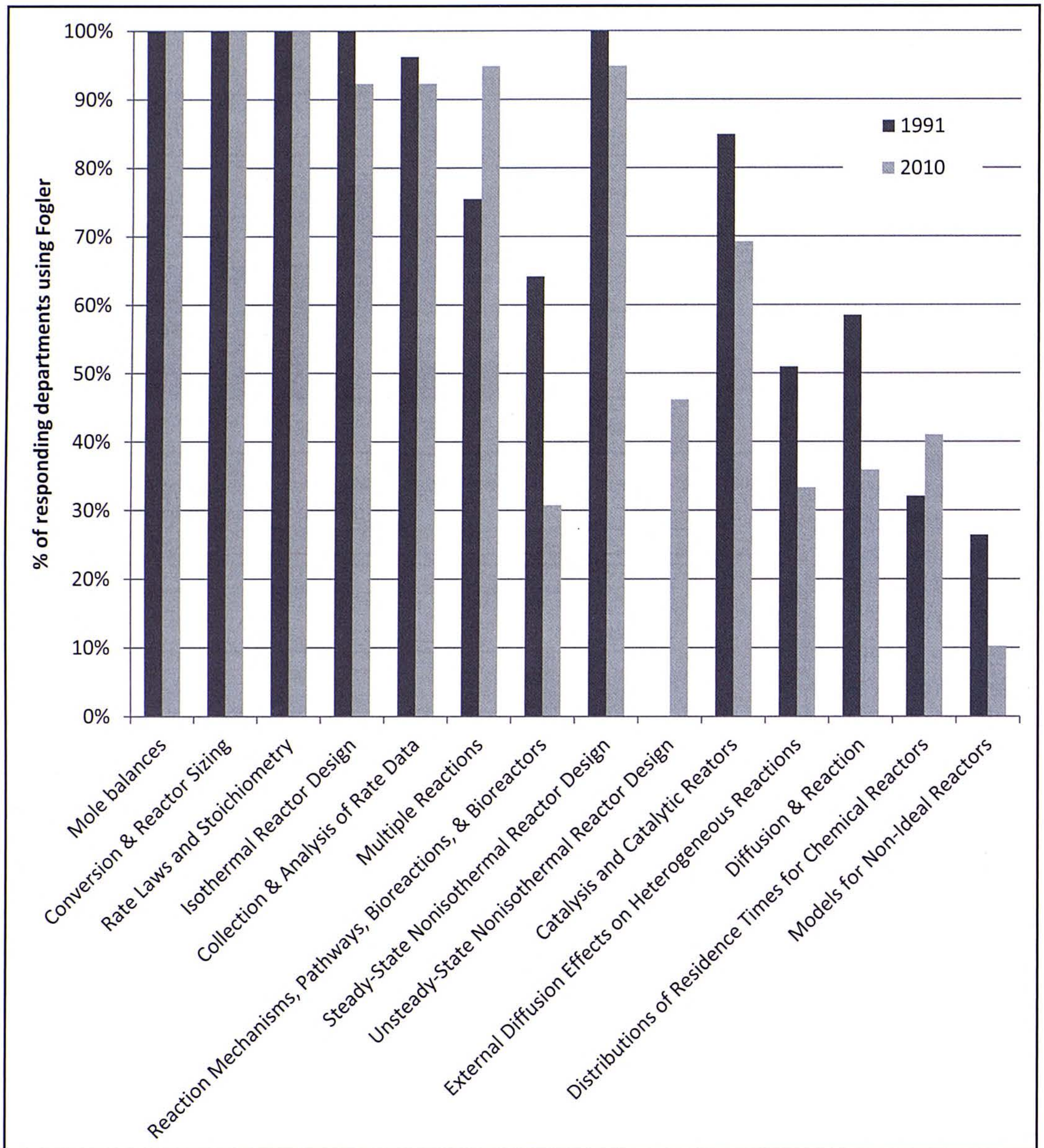

Figure 11. *Chapter topics taught as organized by Fogler's text. When editions have different titles, similar chapters have been combined. Data for 2009-2010 as reported by instructors.*

Along with changes in the core coverage, there have been changes in when core topics have been taught. The 1971 survey reported that 13% of programs covered the subject of reaction equilibrium in the CRE course. In 1984, this increased to 65% of responding departments indicating reaction equilibrium was taught in the CRE course, with 12% indicating it was taught in the thermodynamics course or sequence. Twenty-two percent responded "other" or "both." In 2010, only 5% of programs indicated the subject was covered in CRE.

Another topic considered in previous surveys is the theory of absolute reaction rates (a statistical mechanics approach). In 1974, about 58% of programs covered the theory of absolute reaction rates. The 2010 survey indicated 78% of programs covered the topic. Coverage of other emerging topics in CRE in the 2010 survey is presented as Figure 12.

Chemical engineering programs are likely to use this course for ABET outcomes assessment. The fraction of reporting programs using this course for ABET a-k outcomes is shown in Figure 13.

COMMON CONCERNS

Survey respondents were asked what they believed were the biggest issues encountered by students taking this course. The majority of responses indicated the following common challenges:

- *ODE solving skills*
- *Mathematical software skills*
- *Chemistry preparation*
- *Unsteady-state conservation law writing*
- *Dependence on "design equations" rather than fundamental conservation laws*

Concern over transfer of prerequisite knowledge to core courses is common, and is reflected in the list, as is the ongoing tension between engineering approximation and solution based on first principles.

THE ROLE OF INSTRUCTOR

Instructors often take different approaches to teaching. For many responding to the survey, instructors viewed themselves as a guide or facilitator, bringing students through the textbook material in a "rational way" and providing alternate explanations to the text. Others attempt to give a "big picture" view, tying various elements of the course (and the curriculum) together into a cohesive whole. For some, the role shifts as needed, from mentor to partner to coach depending on the student and the situation. Some instructors express the need for them to make the topic interesting and accessible, and to develop new examples and homework problems. The role as an evaluator was also commonly noted. Some indicate their role is to build on the textbook and not repeat what is explained well. Introduction of modern tools for design and simulation was emphasized by others. Another role cited by several instructors is a need to translate the ideality of a textbook to the challenges of the real world, including imperfect data, equipment failures, variability in feed stocks, management issues, etc.

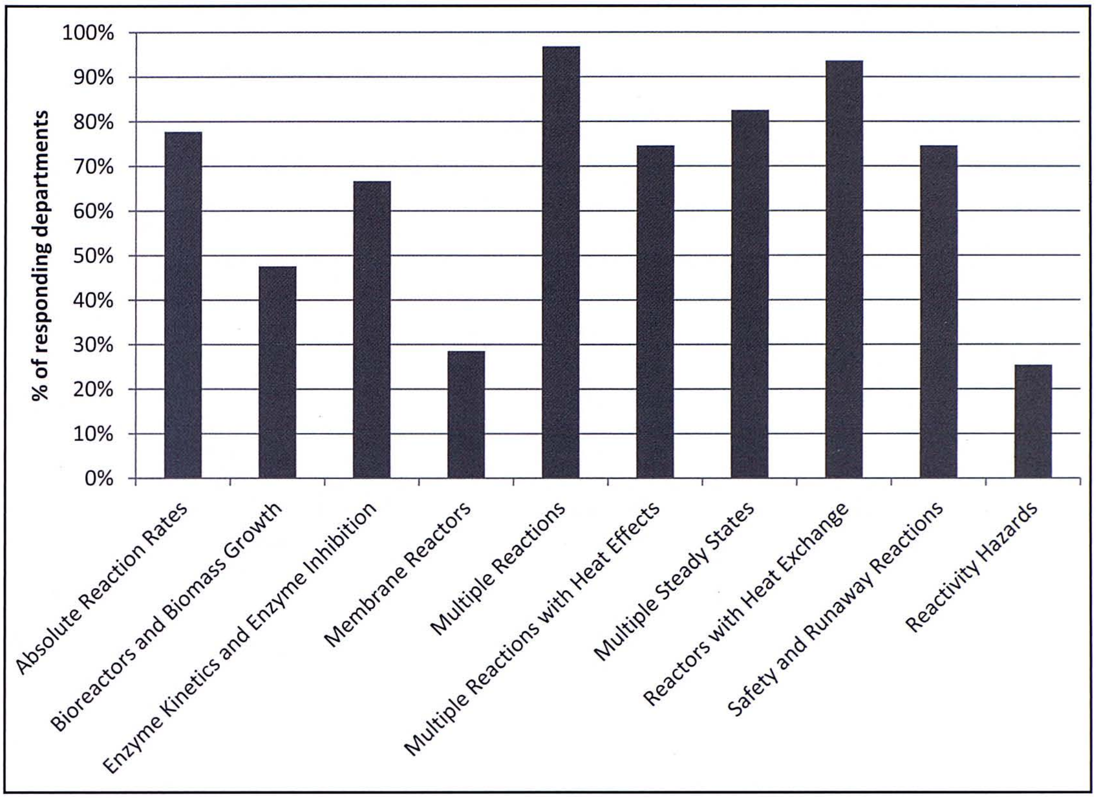

Figure 12. *Coverage of modern topics in CRE courses for 2009-2010 as reported by instructors.*

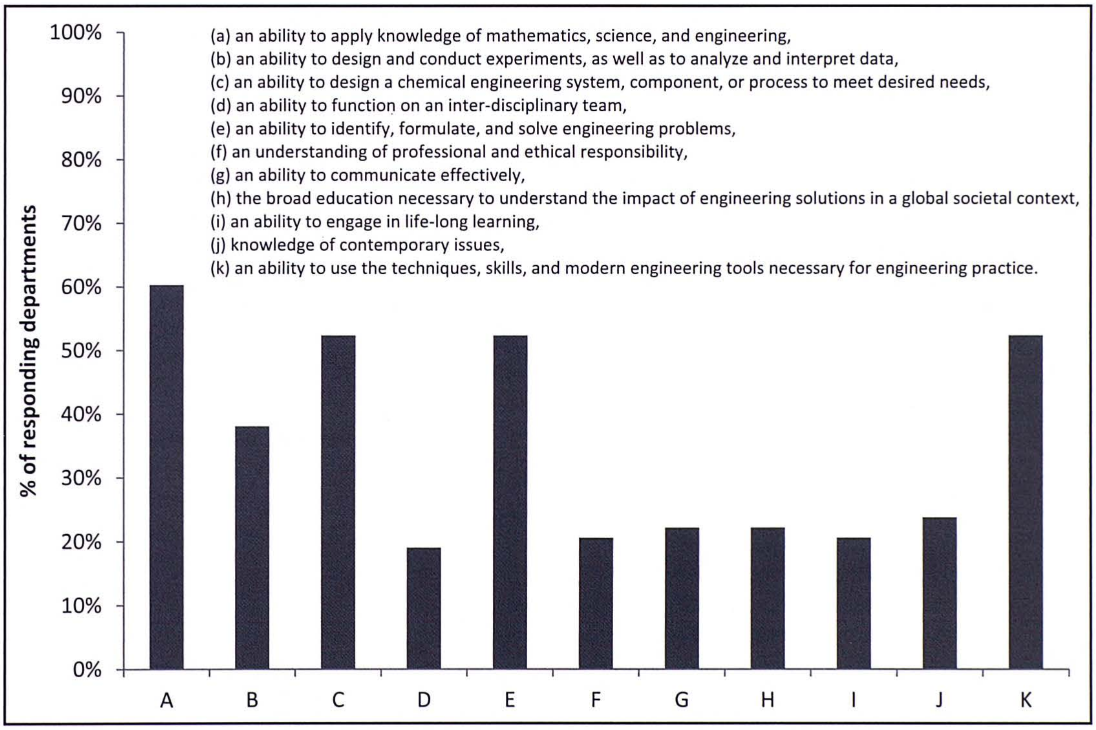

Figure 13. *Percent of programs using the CRE course as part of their ABET EC2000 assessment process for program outcomes. Data for 2009-2010 as reported by instructors.*

EFFECTIVE TEACHING METHODS

As part of the survey, responding instructors were asked to share some of the teaching methods and resources they believe were most effective. To follow up on those responses, a panel-led discussion was held at the 2010 AIChE Annual Meeting in Salt Lake City to build the description of methods and responses to the aforementioned concerns with teaching the course. Synthesized from both the survey and the discussion, the following topical elements were highlighted:

- ***Emphasis on fundamentals.*** *Starting from a mass balance rather than working from "design equations" was recommended. Algorithmic approaches are effective. Peer-to-peer instruction in problem sessions is effective.*
- ***Safety.*** *While safety has always been an important element of the course, it is likely to become even more critical in response to changes to ABET Chemical Engineering program criteria. Chemical reactivity hazard analysis will likely become a major topic in the course (or in a dedicated safety course) while runaway reactions will continue to be emphasized. There are opportunities to develop resources to aid teaching these topics. Safety should also be brought into class discussion frequently in the context of "what if" questions.*
- ***Software.*** *Fogler pioneered the development of CRE-related tutorial software in the 1990s and recently updated those resources. Finite element simulations and other CFD software can lead to effective introductions to more realistic reactor modeling. Spreadsheet-based rate simulators are available, as are simulations for complex reaction pathways with effective kinetics. The emergence of computational software has made complex systems like multiple reactions accessible,*[1] *but training on how to use the software effectively remains an issue. Programming, including working from a partially completed program or one with significant errors, can be effective in teaching concepts like examining the role of activation energy in multiple reaction systems or hot spots in a PFR. Others focus on setting up problems for computer solution in class, then executing the solution software. Having TA's run help sessions for software can be effective.*
- ***Laboratories.*** *Numerous laboratory systems were named, including: yeast fermentation; horseradish peroxidase marking; crystal violet dye decomposition; temperature-controlled flash photalysis (isomerization); RTD using dye injection; electrochemical water decomposition; alcohol decomposition/digestion; air bag detonation; ChemE Car design or demonstration; saponification of ethyl acetate in a batch reactor, a CSTR, and two CSTRs in series; methanol-to-gasoline conversion; photo-catalytic destruction of aqueous pollutants; catalytic isomerization of butane in a PBR; reaction of diazydiphenylmethane with substituted carboxylic acids; reaction between sodiumthiosulfate and hydrogen peroxide in an adiabatic batch reactor; hydrolysis of crystal violet dye in an isothermal tubular reactor and a CSTR; isomerization of sulfite in a Parr reactor; alkaline fading of phenolphthalein in a batch reactor; hydrogen peroxide/sodium thiosulfate in an adiabatic batch reactor; catalytic methanol oxidation on a Pt wire; kinetic measurements of alkaline phosphatase (ALP)-catalyzed dephosphorylation of p-NPP in a CSTR; and reaction kinetics governing lactose conversion of dairy products. Note that the 1974 and 1984 survey reports include a list of all experimental systems reported by the respondents.*
- ***Mathematics.*** *Peer teaching was suggested as an effective way of developing student math skills. Game show approaches for in-class problem solving can be effective. A background in probability/statistics is becoming increasingly important in applying risk analysis to reactive systems, to catalytic reactions, and for sensitivity analysis. Propagation of error is another area where preparation could be improved. Some would argue that analytical mastery should be demonstrated before computational methods are used.*
- ***Economics and other practical considerations.*** *Some assert that discussing economics is impractical before formal coverage in a process design course, while others state it is important to bring practical limitations on reactor design and operation into the discussion during the course. Material handling issues (such as polymers) should be discussed. Some suggest having co-op students tell stories related to industrial practice. The role of rating existing equipment tends to be underemphasized compared to design. Team projects requiring reuse of equipment, equipment profiling, and detailed specifications are recommended. Others seek to replace generic reactions (A+B → C) with real chemical systems.*
- ***Emerging topics.*** *While exposure to bio- and nano- topics will continue to be important, energy will likely emerge as an area of emphasis in the short term. Ethics and safety will also likely increase in emphasis. Simulation-based engineering is developing as an important area of study and practice.*

The following list of effective teaching elements and suggestions represents a combination of the discussion and the survey.

- ***Critical thinking and conceptual learning.*** *The importance of always asking students "why," "how," etc., was emphasized. Many would argue the conceptual understanding of CRE is often more valuable than the computational aspects. Concept questions that can be used with (or without) classroom response devices (clickers) are available at* <http://www.learncheme.com> *courtesy of a project led by John Falconer. Additional conceptual-learning resources are available as part of the AIChE Education Division Concept Warehouse,* <http://cw.edudiv.org>.
- ***Group work.*** *Significant time is devoted to group problem solving by many instructors. Some formalize roles within the group: Thinker - is asked to solve problem, but does not get to use book or paper and pencil. Source of Knowledge - has access to book and problem statement;*

may only share verbally. And Recorder - the only one in the group with paper/pencil/calculator. They all must work together to solve the problem. Thinker will also be the group spokesperson to the rest of class.

- ***Asynchronous lecture.** One instructor uses pre-recorded lectures for instruction and spends class time on learning activities that build on the assigned preparation. A wide range of active learning exercises is then used, including teaching by analogies, inquiry activities, minute papers, contexts, debate, panel discussion, role playing, etc. Other instructors teach the course as a self-paced course with a computerized examination system. Another common approach is recording and archiving lectures live and posting for later review.*
- ***Novel homework approaches.** For one instructor, homework is an individual/team effort, where the team has the submission graded and individuals submit their own solution to verify effort. The grade is assigned based on a combination of the team and individual contribution. Another instructor requires written reflective assessment of homework submissions. Literature reviews and analysis are common.*
- ***Project- and/or Problem-Based learning** approaches are cited by several instructors.*

Analogies were often suggested as means of effective teaching. Particular examples include:

- *Site balances are compared to the number of chairs in a room.*
- *Batch reactors are compared to cooking vessels.*
- *Elementary reactions are compared to the likelihood of people (or pool balls) colliding. Two will hit fairly often, but three-way collisions are exceedingly unlikely.*
- *Tracer experiments are compared to observing a person in line at Space Mountain and then watching for when the same person emerges from the exit.*
- *The slab approximation for solving the n-order Theile modulus problem is as though a catalyst pellet has the peel of an orange in which all reactions happen; we then peel our pellet and "press" it flat into a flat slab.*

Some of the analogies take the form of in-class activities:

- *Rate limiting step: one student starts with a deck of cards and slowly deals them to a second student who passes them to a third who has to walk all the way across the room to pass each one to a fourth, etc., to "explain" a rate-limiting step.*
- *Residence time distributions: An activity where the students "own" a nightclub and want to know how long people stay at the club (too short and they don't spend, intermediate and they spend, too long and their spending dies off).*

The learning environment, both physical and contextual (what is done in class), can also play a role in helping students learn.

- *Active learning, as seen in many of the responses already detailed, is common and effective.*
- *Many instructors are deliberately reducing lecture and increasing discussion and group problem solving.*
- *Computer projectors are typically available, and many instructors project their solutions to problems and explore the models developed in class. PowerPoint is extensively used, as are online videos and images of real reactor systems. Some environments allow students to solve problems on computers alongside the instructor.*
- *Some classes are taught in a studio environment to facilitate interaction among students.*

In addition to program-determined outcomes, individual instructors tend to have areas of emphasis corresponding to their individual perceptions of importance of class topics. While no single course emphasizes all of these, individual goals for this course include:

- *Application of conservation laws*
- *Bioreactors*
- *Capstone integration*
- *Cost concerns*
- *Distinguish between ideal and nonideal reactors*
- *Distinguish between reaction-dependent factors and reactor-dependent factors*
- *Distinguish between stoichiometry and rate law*
- *Estimation methods*
- *Experimental analysis of rate laws*
- *Fundamentals of catalysis and surface reactions*
- *Industrial chemistry*
- *Intuition on reactor operation*
- *Numerical methods*
- *Optimization*
- *Overcoming equilibrium limitations*
- *Problem-solving skills*
- *Reaction system design (reactor + heat exchange + recycle)*
- *Reactor sizing*
- *Simulation skills*
- *Use of fundamental thermodynamics*
- *Utility of microscopic and macroscopic descriptions*

CONCLUSIONS

In many ways, Chemical Reaction Engineering may be taken as a bellwether of chemical engineering education in practice. It is one of the few courses taken exclusively by chemical engineering students; teaching practices in this course are therefore a good indicator of what is "typical" for the chemical engineering undergraduate experience.

The CRE course appears to be in the midst of a shift. It is moving earlier in the curriculum, as more programs offer the course in the junior year. The coverage is evolving, driven by technology (computational capability, FEM/CFD), by ABET (safety), and by other emerging topics. Despite the changes, the core coverage of the course has remained fairly constant.

Class sizes appear cyclical over the past several decades and appear to currently be around a local maximum, mirroring the national trends in engineering and chemical engineering enrollments.

Commonly accepted and literature-proven methods of instruction are commonly applied within the course. Use of "clickers" is common both as formative assessment and as a teaching tool. Resources supporting an emphasis on conceptual learning, such as publication of conceptual questions online, are increasing. Problem-based learning approaches and laboratories are available, although not in the majority of programs. Many programs are utilizing improved simulations of laboratories to obtain learning outcomes similar to laboratory exercises. Active learning approaches are widespread and varied, and those who use them are satisfied that they are effective.

ACKNOWLEDGMENTS

The authors would like to thank all of the instructors who completed this survey; the department chairs who passed on the request; and the University of Kentucky College of Engineering computing services, which hosted the survey. We would also like to acknowledge the assistance of Professor Don Woods of McMaster University for his review of the survey draft and continuing advice.

The full response data set is available from author David Silverstein upon request. The previous survey reports for this course are available on the AIChE Education Division website, <*www.edudiv.org*>.

REFERENCES

1. Fogler, H.S., and M.B. Cutlip, "Chemical Reaction Engineering (CRE) Education: From the Era of Slide Rule to the Digital Age," Proceedings of the 2008 AIChE Centennial Topical Conference on Education; American Institute of Chemical Engineers; November 2008
2. Silverstein, D.L., and M. Vigeant, "How We Teach: Kinetics and Reactor Design," Proceedings of the 2011 Annual Meeting of the American Society for Engineering Education, American Society for Engineering Education; June 2011
3. Eisen, E.O.,"Summary Report: Teaching of Undergraduate Kinetics," American Institute of Chemical Engineers; Dec. 4, 1974
4. Eisen, E.O., "Summary Report: Teaching of Undergraduate Reactor Design," American Institute of Chemical Engineers; Nov. 28, 1984
5. Eisen, E.O., and M.C. Ragsdale, "The Teaching of Undergraduate Kinetics/Reactor Design," American Institute of Chemical Engineers; Nov. 14, 1991
6. Silverstein, D.L., M. Vigeant, D. Visco, and D. Woods, "How We Teach: Freshman Introduction to Chemical Engineering," Proceedings of the 2010 Annual Meeting of the American Society for Engineering Education (2010)
7. American Society for Engineering Education "Engineering College Profiles and Statistics 2010," accessed online at: <http://profiles.asee.org/> (accession date July 8, 2011) ❐