RANKING GRADUATE PROGRAMS
Alternative Measures of Quality

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Assessing the relative quality of graduate programs is of great interest to policy makers, academic admin istrators, prospective students, employers of graduates, alumni, and the general public. Rankings by federal advisory panels[1] and the popular press[2] are widely quoted, but despite the importance assigned to the rankings, there has been little critical, detailed analysis of their relevance and accuracy. In this paper we will present an analysis of the most prominent of these reports,[1] especially as it relates to chemical engineering programs. Although our discussion is confined to chemical engineering, we believe that the general conclusions and methods are also relevant to the other engineering disciplines.

The National Research Council (NRC) in 1995 released a massive study[1] of research doctorate programs in the U.S. It was the product of a committee of eighteen academics from various disciplines and is a follow-on study of a similar report issued in 1982. The report contains reputational rankings, based on a survey of graduate faculty, as well as an impressive amount of factual data from several independent sources. Unfortunately, most attention has been focused on the survey results—in particular the reputational ranking based on perceived faculty quality. This is apparently due, at least in part, to the method by which the data were displayed in the report and the normal tendency to simplify complex data sets into a single, easily understood, quality index.

Several aspects of the NRC report have caused concern. (See, for example, the summary article by Mervis.[3]) One striking feature of the results, noted by the authors, was the "remarkable stability among programs rated in the top and bottom quarter" between the 1982 and 1995 reports. Another striking feature was the heavy reliance on the survey

Editorial Comment . . .

A strength of the engineering education system in the United States is its diversity. It is evident in such characteristics as student demographics, college missions and sources of funding, enrollment levels, research strengths, collaborations, and curricula. A positive outcome of our system is the diverse pool of graduates produced to meet the varied and dynamic workforce needs of the world. Choices, however, are being made that can significantly impact programs. Industry selects schools for recruiting visits; students commit to pursue graduate or undergraduate degrees at specific schools, and private and public foundations and agencies award grants, contracts and gifts to selected institutions. The perceived quality of an institution is often an important factor in these decisions, and rankings by institution, college, or degree program contribute to defining perceptions.

In recent years, chemical engineering departments have been asked to assess the quality of their programs to direct improvement strategies. This movement is being driven internally as well as externally by regional and national accreditation entities and by funding agencies (*e.g.*, state governments). Ideally, rankings would directly assess the quality of graduates and the improvement in students while they were enrolled. Since no method to do this has been devised, ranking schemes typically use a combination of numerical program data and peer ranksing to determine a score instead of doing a direct assessment. Although the efficacy of this approach is still being debated, it has increased the importance of peer comparison and the availability of program data. This issue of *CEE* presents a paper by Angus, Edwards, and Schultz that proposes alternative measures of graduate program quality. Not surprisingly, an extensive review process revealed that the subject of rankings is a contentious issue. The reviewers as well as the authors identified many of the shortfalls in assessing the quality of something as complex, multidimensional, and subjective as graduate programs. Identified issues included the establishment of false goals, for example publishing papers in smaller segments or of lesser quality, or hiring faculty in publication-intensive research areas simply to increase the publication count, all of which would increase ranking but could likely decrease program quality. Another issue was that inaccurate or inappropriate data would undermine the conclusions. Examples include the counting of non-competitive research funding (*e.g.*, state funding) and the use of a limited set of journals for citation searching or a limited set of societies in award counting that would not recognize programs with an emphasis on emerging research areas.

This paper presents a sound analysis of the recent NRC ranking, and many of the conclusions as well as the analytical approach can be extended to other ranking schemes. Although the proposed alternative measures of quality may be open to criticism, the authors clearly show the sensitivity of rank order to the selected set of measures and to weighting algorithms (*e.g.*, intensive vs. extensive). We hope that this paper will increase awareness of the shortfalls of any approach to ranking and help one gauge what can and cannot be ascertained from a ranking. We do not believe that a composite index can be developed to accurately measure the relative quality of chemical engineering degree programs in our complex graduate education system, nor is it desirable to drive programs to conformity. We recognize, however, that ranking schemes have increased their presence in our profession and to ignore their impact would be a mistake. We hope that this article will stimulate serious discussion in the community. ❐

results, which were used to generate reputational rankings rather than "quantitative" measures of quality. Another concern, quite apparent to engineers and scientists, was the minimal distinction drawn between intensive (size independent) and extensive (size dependent) measures of quality. Although the report included a number of statistical tests of the data, no detailed analysis of sources of error in the data sets was provided. Finally, there was no assessment of program quality based on student outcomes in their subsequent professional life. The committee was aware of many of these concerns and, in fact, was unable to address some of them for lack of time and resources. The committee was also aware that the report might be used in superficial ways that were not intended.

The NRC report is being used by deans, legislators, and foundations in the allocation of resources and in other critical decisions. It is therefore useful to understand the report and to critically examine its conclusions. In this paper we will give an analysis of the data for the chemical engineering programs covered in the report. We will also give alternative rankings using data from the NRC report and other sources. *We emphasize that the rankings presented here are meant only to illustrate the methods employed and to reach general conclusions. Because of limitations in the data available to us, the position of a particular individual program in the rankings should be treated with caution.*

TABLE 1
Survey Questions Used for the NRC Report[1]

B1 Familiarity with work of Program Faculty
1. ___ Considerable familiarity
2. ___ Some familiarity
3. ___ Little or no familiarity

B2 Scholarly Quality of Program Faculty
1. ___ Distinguished
2. ___ Strong
3. ___ Good
4. ___ Adequate
5. ___ Marginal
6. ___ Not sufficient for doctoral education

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9. ___ Don't know well enough to evaluate

B3. Familiarity with Graduates of this Program
1. ___ Considerable familiarity
2. ___ Some familiarity
3. ___ Little or no familiarity

B4 Effectiveness of Program in Educating Research Scholars/Scientists
1. ___ Extremely effective
2. ___ Reasonable effective
3. ___ Minimally effective
4. ___ Not effective

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9. ___ Don't know well enough to evaluate

B5 Change in Program Quality in Last Five Years
1. ___ Better than five years ago
2. ___ Little or no change in the last five years
3. ___ Poorer than five years ago

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9. Don't know well enough to evaluate

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Robert V. Edwards *received his PhD from Johns Hopkins University in 1968 and took a post-doctoral position at Case Western Reserve University to work on the then-new field of laser light scattering for transport measurements. He joined the Case faculty in 1970 and has subsequently made numerous contributions to the theory and practice of laser light scattering with collaborators, both here and abroad.*

Brian D. Schultz *obtained his BS in chemical engineering from Case Western Reserve University in 1977. He won a National Science Foundation Fellowship, which he used to pursue his Master's degree at Case, and in the fall of 1998, he began working toward his PhD at the University of Minnesota. Research interests include ternary phase diagrams for low-pressure crystal growth as well as the thermochemical behavior of group III nitrides.*

PART 1
THE NATIONAL RESEARCH COUNCIL REPORT

Methods • The most discussed part of the NRC report is the faculty survey conducted in 1993. Questionnaires were sent to randomly selected faculty and each participant was asked to rank approximately fifty programs. Other than a list of faculty, the participants were provided no other information about the programs. The survey questions are shown in Table 1.

Forty-one graduate fields of study were covered in the NRC report, one of which was chemical engineering. For chemical engineering programs, 206 usable responses were obtained from 361 questionnaires, a 57% response rate. Within chemical engineering, 93 of the 121 engineering departments awarding PhD degrees during the 1986-92 time period were included. These 93 departments produced 96% of the chemical engineering PhDs awarded during that period.

The results of the survey were tabulated in the Appendices to the NRC report. The programs were listed in order in the tables according to the results of the first survey question (the average ranking of faculty quality). This procedure was used in response to complaints that data in the 1982 report were difficult to interpret because programs were listed alphabetically. The result, however, has been to focus on this one single measure of quality, despite the fact that rankings in the other categories (*e.g.*, program effectiveness and visibility) are also provided in the report.

One of the purposes of the committee that compiled the 1995 NRC Report was to expand the "objective" measures developed by prior committees. Some program statistics were provided: number of faculty, number of PhDs granted, number of PhDs awarded to female and minority students and non-citizens, and the average length of time to receive a PhD. Quantitative measures of quality were also provided: 1) percentage of faculty with research support (%SUPP), 2) percentage of faculty publishing during 1986-92 (%PUB), 3) total publications during 1986-92 (PUB), and 4) total citations to published work during 1986-92 (TC). The latter two were also reported on an intensive (normalized per faculty) basis, *i.e.*, PUB/TF and TC/TF (see Table 2 for a description of the terms in the NRC report).

Survey Results • In Table 3 we give the acronyms used in subsequent tables for identification of universities, and in Table 4 we list the graduate programs in chemical engineering as they were rank-ordered by perceived faculty quality (93Q) in the NRC report. This is the order in which the programs are listed in Appendix P of the NRC report.

A striking, but not widely appreciated, feature of the NRC report is shown in Figure 1,* which is a plot of the survey results for faculty quality (93Q) versus program effectiveness (93E). A very strong correlation is evident. For example, R^2=0.97 when the data are fit with the equality (93Q)=(93E). This strong correlation can arise simply because high-quality faculty will produce effective graduate programs. We believe it is far more likely that the respondents did not discriminate between faculty quality and program effectiveness and treated both questions the same. This strong correlation was noted in the NRC report in Appendix O-8 where a Pearson product-moment correlation coefficient of 0.98 between 93Q and 93E was given for chemical engineering. Similar strong correlations between 93Q and 93E were observed for the

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** In Figure 1 and subsequent figures we indicate the square of the degree of correlation by R^2, the coefficient of determination. The magnitude of R^2 is simply described as the fraction of the raw variance in the data set accounted for by using the fitted equation. The plots and values of R^2 were obtained using an Excel spreadsheet.*

TABLE 2
Definition of Terms Used in this Paper

NOTE: In the NRC report, the symbols for the variables referred to both the rank order, and, where applicable, to the average score of the ratings on the scale of 1 to 5. We give both definitions in the list below. The definitions are taken from Appendix P, page 469, and Table 2-4, page 25, of the NRC report. Not all of the categories used in the NRC report were used in this paper. The terms below the dashed line were not used in the NRC report.

93Q	Rank order of "scholarly quality of program faculty." (Average score on a scale of 0 to 5, with 5 representing "Distinguished.")
93E	Rank order of "program effectiveness in educating research scholars and scientists." (Average score on a scale of 0 to 5, with 5 representing "Extremely Effective.")
VIS	Rank order of visibility of the doctoral program (Percentage of the questionnaires that reported some knowledge of the program by an answer other than "Don't know well enough to evaluate" or "Little or no familiarity" to one or more of the five questions.)
TC	Rank order of the total number of citations attributed to program faculty in the period 1988-92. (Total number of citations attributed to program faculty.) Source: Institute of Scientific Information.
C/F	Rank order of the citation density for the program faculty (Total number of citations (TC) divided by the number of program faculty (TF)). Source: Institute of Scientific Information.
PUB	Total number of publications attributed to program faculty for the period 1988-92.
TF	Number of program faculty in fall 1992. NRC Report for calculating PUB/TF and TC/TF; AIChE[9] for calculating HON/TF and SUPP/TF.
HON	Number of honors received by faculty.[6-8] See text for details
SUPP	Total research support from all sources. Source: National Science Foundation.[4]

TABLE 3
Acronyms Used to Identify Universities

ASU	Arizona State University	NEU	Northeastern University	UAZ	University of Arizona	UMOC	University of Missouri-Columbia
AUB	Auburn University	NJIT	New Jersey Inst. of Technology	UCB	University of California-Berkeley	UMOR	University of Missouri-Rolla
BYU	Brigham Young University	NWU	Northwestern University	UCD	University of California-Davis	UMS	University of Mississippi
CIT	California Inst. of Technology	OHU	Ohio University	UCIN	University of Cincinnati	UOK	University of Oklahoma
CLAR	Clarkson University	OKSU	Oklahoma State University	UCLA	Univ. of California-Los Angeles	UPA	University of Pennsylvania
CLMN	Clemson University	ORSU	Oregon State University	UCO	University of Colorado	URI	University of Rhode Island
CMU	Carnegie Mellon University	OSU	Ohio State University	UCSB	Univ of California-Santa Barbara	USC	Univ. of Southern California
COL	Columbia University	PITT	University of Pittsburgh	UCT	University of Connecticut	UTA	University of Texas-Austin
CORN	Cornell University	PLYU	Polytechnic University	UDE	University of Delaware	UTN	Univ. of Tennessee-Knoxville
CSM	Colorado School of Mines	PRU	Princeton University	UFL	University of Florida	UTUL	University of Tulsa
CUNY	CUNY-Grad Sch & Univ Center	PSU	Pennsylvania State University	UH	University of Houston	UUT	University of Utah
CWRU	Case Western Reserve Univ.	PUR	Purdue University	UIA	University of Iowa	UVA	University of Virginia
DUKE	Duke University	RICE	Rice University	UIC	University of Illinois-Chicago	UWA	University of Washington
GIT	Georgia Institute of Technology	ROCH	University of Rochester	UID	University of Idaho	UWI	Univ. of Wisconsin-Madison
IIT	Illinois Institute of Technology	RPI	Rensselaer Polytechnic Institute	UIL	Univ of Illinois,Urbana-Champaign	UWY	University of Wyoming
ISU	Iowa State University	RSU	Rutgers St. Univ-New Brunswick	UKS	University of Kansas	VAND	Vanderbilt University
JHU	Johns Hopkins University	SIT	Stevens Institute of Technology	UKY	University of Kentucky	VPI	Virginia Polytech Inst & State Univ
KSU	Kansas State University	STAN	Stanford University	ULV	University of Louisville	WASU	Washington State University
LEH	Lehigh University	SUNY	State Univ of New York-Buffalo	UMA	Univ. of Massachusetts-Amherst	WPI	Worcester Polytechnic Institute
LSU	Louisiana St. U & A&M College	SYR	Syracuse University	UMD	Univ. of Maryland-College Park	WSU	Wayne State University
MIT	Massachusetts Inst. of Tech.	TAM	Texas A&M University	UME	University of Maine	WU	Washington University
MSU	Michigan State University	TUL	Tulane University	UMI	University of Michigan	WVU	West Virginia University
NCSU	North Carolina State University	UAKR	University of Akron	UMN	University of Minnesota	YALE	Yale University
ND	University of Notre Dame						

other engineering programs. This level of correlation strongly suggests that these two of the five survey questions gave indistinguishable results.

In Figure 2a, we show a plot of perceived faculty quality (93Q) versus faculty size (TF). The value of R^2 is 0.40, suggesting that the survey results for faculty quality are influenced to some extent by program size, but that other factors are also important.

The program visibility (VIS) was defined as the percentage of respondents who reported some knowledge of the program. In Figure 2b we plot the faculty quality (93Q) versus the visibility (VIS). A strong correlation, R^2=0.84, is observed. One cannot prove cause-and-effect relationships through correlation alone; however, these results suggest that the perceived faculty quality (93Q) scores arise, at least in part, because respondents rate highly those faculty with

TABLE 4
Rank Order of ChE Faculty Quality Survey Results (93Q) Given in the NRC Report

Rank Order	*University*
1	University of Minnesota
2	Massachusetts Institute of Technology
3	University of California-Berkeley
4	University of Wisconsin-Madison
5	Univ of Illinois, Urbana-Champaign
6	California Institute of Technology
7	Stanford University
8	University of Delaware
9	Princeton University
10	University of Texas at Austin
11	University of Pennsylvania
12	Carnegie Mellon University
13	Cornell University
14	Univ of California-Santa Barbara
15	Northwestern University
16	Purdue University
17	University of Houston
18	University of Michigan
19	CUNY-Grad Sch & Univ Center
20	University of Washington
21.5	Univ of Massachusetts-Amherst
21.5	Rice University
23	Pennsylvania State University
24	University of Notre Dame
25	North Carolina State University
26	University of Colorado
27	Lehigh University
28	University of California-Davis
29	State University of New York-Buffalo
30.5	University of Virginia
30.5	Georgia Institute of Technology
32.5	Yale University
32.5	Iowa State University
34	University of Florida
35.5	Rensselaer Polytechnic Institute
35.5	Johns Hopkins University
37	Texas A&M University
38	Washington University
39	University of California-Los Angeles
40	University of Rochester
41	Ohio State University
42	Virginia Polytech Inst & State Univ
43	Rutgers State Univ.-New Brunswick
44	University of Pittsburgh
45	Michigan State University
46	Case Western Reserve University
47.5	Syracuse University
47.5	Illinois Institute of Technology
49	Clarkson University
50	Brigham Young University

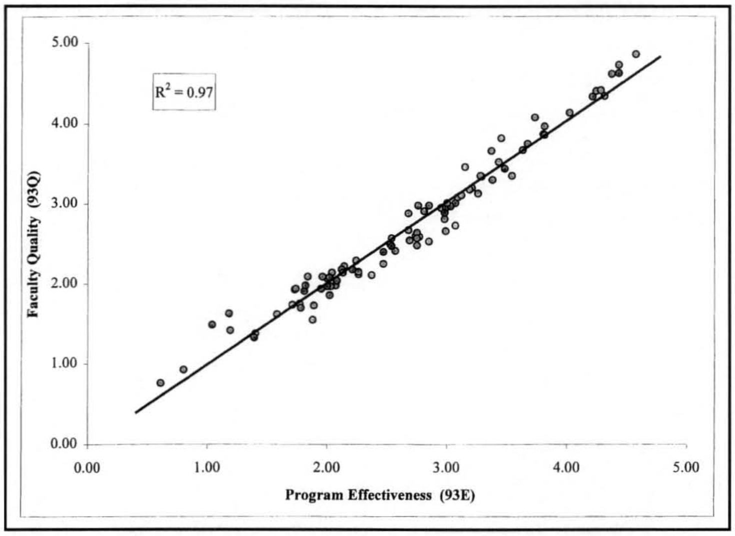

Figure 1. *Survey results of program effectiveness (93E) versus faculty quality score (93Q). R^2=0.97 when fit with (93E)=(93Q).*

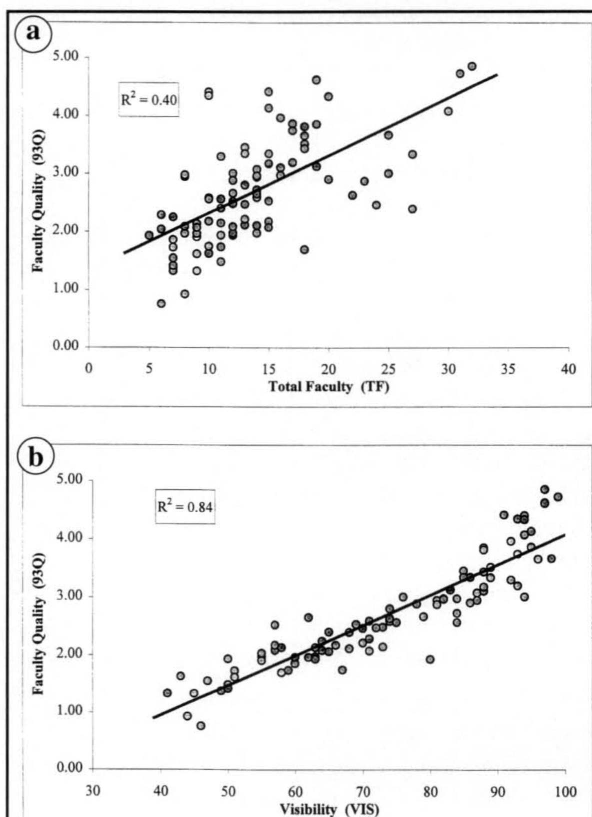

Figure 2.

(a) *Survey results of faculty quality (93Q) versus total faculty (TF). R^2=0.40 for linear fit, y=mx+b.*

(b) *Survey results of faculty quality (93Q) versus visibility (VIS). R^2=0.84 for linear fit, y=mx+b.*

whom they are familiar. If this familiarity arises solely because of the true quality of the faculty, this result is benign; otherwise it is not.

A relatively strong correlation is observed between rank order of visibility and rank order of total citations (R^2=0.67), and a weaker correlation between rank order of visibility and total number of faculty (R^2=0.39). These results are encouraging because they show that smaller departments can have an impact by virtue of their research output. Significant correlations are also found between perceived faculty quality (93Q) and the number of publications (R^2=0.73), number of publications per faculty (R^2=0.64), total citations (R^2=0.71), and citations per faculty (R^2=0.56).

In summary, it appears that the respondents made no distinction between the survey questions on faculty quality (93Q) and program effectiveness (93E). To some extent, sheer size influenced the quality rankings and respondents gave high ranks to programs with which they were familiar. Strong positive correlations exist between the survey results of faculty quality and the publication and citation rates.

PART 2 ALTERNATIVE METHODS OF RANKING

Alternative Measures of Quality • Four extensive measures of program quality are used: 1) Number of publications, 2) number of citations to publications, 3) research funding, and 4) faculty honors. In addition, each of these extensive measures is normalized by the number of faculty to provide four intensive measures of quality. We use these data to develop alternative rankings of programs based on both the extensive and intensive criteria. We also provide a final composite ranking based on the extensive and intensive rankings. We are quite aware that these so-called "objective" measures are imperfect, and we will attempt to point out potential problems with each of the measures we use.

Quantitative measures of quality are not new. Some were used in the NRC Report as mentioned above. Also, the often-maligned *U.S. News and World Report*[2] used a lumped score in which

TABLE 5
Programs not Considered in Final Rankings Because of Lack of Data on Research Support

Brigham Young University	University of Louisville
City University of New York	University of Maine
Duke University	University of Mississippi
Illinois Institute of Technology	University of Notre Dame
Northeastern University	University of Rhode Island
Rice University	University of Tulsa
University of Akron	University of Wyoming
University of Idaho	Washington University
University of Kansas	Worcester Polytechnic University

TABLE 6
Rank Order and Scaled Scores of ChE Graduate Programs Using Extensive Criteria

	Publications		Citations		Support		Honors		Extensive Composite	
University	Score	Rank	Score	Rank	Score	Rank	Score	Rank	Score	Rank
UMN	100.0	1	100.0	1	76.6	3	77.9	2	354.5	1
MIT	79.2	2	65.0	3	100.0	1	100.0	1	344.2	2
UTA	76.6	3	76.6	2	55.6	5	72.6	3	281.4	3
UCB	50.3	4	45.2	4	13.4	41	56.1	6	165.0	4
UDE	34.2	6	23.3	8	30.7	12	68.3	4	156.6	5
UWI	34.1	7	16.2	19	41.6	7	58.6	5	150.6	6
TAM	22.8	24	6.4	45	77.8	2	21.8	27	128.7	7
PSU	25.7	17	13.0	24	23.0	19	54.0	7	115.7	8
UCLA	43.4	5	39.6	5	12.2	44	18.7	35	114.0	9
UCSB	27.6	13	24.9	7	28.2	13	32.5	16	113.2	10
PRU	21.0	27	17.5	16	25.7	16	46.9	10	111.1	11
NCSU	22.6	25	16.8	17	35.9	9	35.0	12	110.4	12
NWU	24.7	20	13.7	23	13.1	42	52.8	8	104.3	13
PUR	34.0	8	21.4	9	26.0	15	20.3	32	101.6	14
STAN	27.6	13	27.7	6	25.4	17	20.3	31	101.0	15
UMI	28.4	11	18.8	13	21.2	24	32.0	17	100.4	16
CIT	24.0	21	17.9	15	21.7	23	29.8	20	93.4	17
UIL	25.7	17	18.3	14	15.4	34	34.0	15	93.4	18
CORN	30.2	9	19.0	12	21.9	22	21.8	27	92.9	19
LEH	30.2	9	20.3	10	23.9	18	17.2	37	91.5	20
UPA	26.1	16	19.3	11	8.4	56	35.0	12	88.7	21
CMU	18.9	30	9.6	38	10.7	48	47.6	9	86.8	22
GIT	28.2	12	10.3	35	26.7	14	20.8	29	86.0	23
SUNY	23.8	22	14.8	22	10.0	50	34.1	14	82.6	24
CWRU	12.0	50	15.8	21	32.2	11	22.4	25	82.3	25
UMA	19.1	29	12.1	26	11.9	45	35.3	11	78.3	26
LSU	24.9	19	11.1	31	22.1	21	16.5	39	74.8	27
UCO	16.5	33	9.4	39	16.9	31	31.9	18	74.7	28
UTN	3.7	87	0.5	91	61.6	4	8.5	53	74.3	29
UWA	27.6	13	16.5	18	14.4	37	13.8	43	72.3	30
UCD	23.5	23	15.8	20	8.8	53	24.0	24	72.1	31
JHU	15.1	36	11.1	32	34.4	10	11.1	48	71.6	32
UUT	22.5	26	11.1	32	21.2	25	16.5	39	71.3	33
UOK	11.8	51	7.9	44	51.6	6	0.0	83	71.3	34
UH	12.2	48	5.3	52	23.0	20	27.2	21	67.7	35
OSU	18.5	31	9.2	40	11.2	47	26.7	22	65.6	36
RPI	17.3	32	9.9	37	15.3	35	20.2	34	62.7	37
PITT	16.4	34	5.8	48	18.9	29	18.1	36	59.2	38
ISU	12.6	44	12.2	25	8.7	55	22.4	25	55.9	39
UVA	14.3	38	10.0	36	10.4	49	20.3	32	55.0	40

Average of Extensive Composite Scores for All Universities - 71.85

40% was based on a reputational survey of deans and members of the National Academy of Engineering. The remaining 60% was derived from quantitative measures of research support, faculty honors, and student selectivity. The *U.S. News and World* report also included both extensive and intensive measures of quality.

We have included only the top forty programs in the extensive, intensive, and composite rankings. Our purpose is to focus on alternative methods of ranking rather than the rank order itself. We have no wish to identify any program as being of low quality.

Publications and Citations • We use both the total number of faculty publications (PUB) and citations to published papers (TC) from the NRC report as extensive measures of research quality. The same variables normalized by the total number of faculty (TF) are used as intensive measures of research quality. We recognize these are imperfect measures. For example, research with the longest range and most profound impact may go unnoticed for decades. Also, it is difficult to agree on what constitutes a publication, and there is a proliferation and duplication of research papers of marginal merit. The number of times a research paper has been cited is a summary judgment, albeit imperfect, of its relevance and importance. But papers with classic errors (for example, cold fusion) may attract numerous citations. More significantly, a single review paper or a paper describing a widely used test or procedure can generate an inordinate number of citations not closely related to research quality. Finally, certain sub-fields within chemical engineering may more easily produce publishable results than others.

Research Support • The NRC report contained data on the percentage of faculty that received research support (%SUPP) and the percentage of faculty that published (%PUB). We found these variables provided little discrimination, especially between high-ranked programs, and we did not use them in our analysis. Instead, we elected to use total research support from all sources (SUPP) collected by the National Science Foundation[4] as an extensive quality measure. These figures were used without modification.* We emphasize that the compilation reported by the NSF is meant to be complete; it includes state support and support from other federal agencies, industry, and foundations. We also note that total research support is one of the primary measures used in recent scholarly studies of the relative quality of research universities.[5]

The data in the NSF report are reported by the individual institutions and may not be reported on a similar basis; research support from ancillary research institutes or unrelated programs may be included in some cases. Also, the amount of state support for research may not be uniformly reported.

Eighteen chemical engineering programs in the NRC report were not listed in the National Science Foundation report. There is no indication whether this is because no data were submitted by these programs or whether they had too little research income to appear on the table (only the top 100 engineering programs were included in the table). Rather than estimate the research support from other sources, we excluded these programs from our rankings. The programs that were excluded are listed in Table 5.

Faculty Honors • Inexplicably, faculty honors were not used as a quality index for engineering and science programs in the NRC report; they were used, however, in the NRC rankings of programs in the arts and humanities. There are certain categories of honors and awards for chemical engineering faculty that can easily be tabulated. For junior faculty we used the number of recipients of NSF Career Development Awards, NSF Young Investigator awards, and Presidential Investigator awards over the period 1988 to 1996;[6] for mid-career faculty we used winners of the principal AIChE awards from 1987 to 1996;[7] and for senior faculty we use the sum of the current number of National Academy of Engineering members[8] plus one-half of the number of Fellows of the AIChE.[7] This arbitrary choice is based on the observation that there are approximately twice as many AIChE fellows as NAE members in the departments surveyed. Retired and emeritus faculty were excluded. The three categories (junior, mid-career, senior) were scaled to give each equal weight. We believe that including only AIChE honors and awards over-emphasizes the traditional areas of chemical engineering. In future rankings we suggest including honors and awards from other professional organizations (*e.g.*, the American Chemical Society, the Electrochemical Society, and the Materials Research Society).

Alternative Rankings • The numerical data in each extensive category (Publications, Citations, Support, and Honors) were scaled so the maximum value in each category was 100. The total extensive score for each program was obtained by summing the four scores for each extensive category. The overall extensive rank order was determined from these summed scores (see Table 6). The programs are listed in Table 6 in the order of their total extensive score.

The intensive scores in each category for each program were obtained by dividing the extensive scores by the appropriate number of program faculty. For calculation of PUB/TF and TC/TF, all data were taken from the NRC report. For calculation of HON/TF and SUPP/TF, the data were taken from references 4,6,7,8, and 9. The intensive scores were also scaled so that the maximum value in each category was 100. A total intensive score was obtained for each program by summing the scaled intensive scores of the four categories. The programs are listed in Table 7 in the order of their total intensive score.

* *We made one exception to this generalization. For our own university, we removed the expenditures of the Macromolecular Science Department from the NSF figures. This lowered the CWRU extensive ranking and left the intensive ranking unchanged. We were unable to make a similar correction for other programs.*

It is tempting to use the intensive rankings in Table 7 as a measure of the average, individual quality of the program faculty. But one should be cautious in doing so, especially for the smaller programs. In some cases the average intensive score is heavily influenced by the activities of one or two particularly strong individuals. This effect was measured in the NRC report by the Gini coefficient, which is a measure of the non-uniformity of the distribution of scores among the individuals. Since we did not have access to the raw data, we could not make this estimate.

A composite extensive plus intensive ranking was also calculated. A simple summation of the total extensive plus intensive scores gave undue weight to the intensive scores. We rescaled the intensive total scores to give the same average score as the extensive scores. A composite extensive/intensive score was calculated for each program using the total extensive score and the rescaled intensive total score. For example, for MIT the composite extensive/intensive score was obtained from

$$344.2 + \frac{71.85}{130.66}(312.1) = 515.8$$

This procedure gave the same overall weighting to the extensive and intensive scores. The composite extensive/intensive scores and rankings are given in Table 8.

It is most appropriate to compare programs using the separate extensive and intensive measures in Tables 6 and 7. Nevertheless, the composite extensive/intensive ranking in Table 8 has value. For example, when making a choice of a graduate program, a prospective student will make an integrated assessment of both extensive and intensive measures. Small programs that are rated very highly on a per-faculty basis may have a limited range of course work and research options; large programs with high extensive scores may not have the desired level of individual faculty quality. A composite score also permits comparisons with other lumped scores—for example, the *U.S. News and World* report rankings.

Sensitivity and Error Analysis • The sensitivity of the rank ordering to changes in the extensive data sets (Publications, Citations, Support, and Honors) can be calculated by calculating Δ ln X($\cong \Delta$X/X) for each of the rank ordered data sets. We show plots of these results in Figure 3. For example, the value of Δ ln (TC) is the fractional change in number of total citations required to change one place in the rank order. In the middle range, the average fractional change required to move one place in the rank order of citations is approximately 0.03; however, greater fractional changes (over 0.30) are required to move one place in the rank ordering at either extreme. Similar behavior is observed for the other extensive variables, also shown in Figure 3. These results show that while it is relatively easy to move in the middle range of rank orders, it will be more difficult for programs to move

TABLE 7
Rank Order and Scaled Scores of ChE Graduate Programs Using Intensive Criteria

	Publications/Faculty		*Citations/Faculty*		*Support/Faculty*		*Honors/Faculty*		*Intensive Composite*	
University	*Score*	*Rank*	*Score*	*Rank*	*Score*	*Rank*	*Score*	*Rank*	*Score*	*Rank*
UMN	100.0	1	100.0	1	56.7	11	69.5	13	326.2	1
UTA	81.7	4	81.7	3	58.3	9	91.8	4	313.5	2
MIT	81.7	4	67.1	5	74.1	6	89.2	6	312.1	3
STAN	88.3	2	88.7	2	63.9	8	61.5	19	302.4	4
UCB	84.8	3	76.2	4	19.8	47	100.0	1	280.8	5
CIT	77.0	6	57.3	6	54.7	12	90.2	5	279.1	6
UWI	57.4	10	27.4	27	58.2	10	98.8	2	241.8	7
JHU	60.4	8	44.3	10	96.2	4	37.4	32	238.3	8
CWRU	38.3	33	50.4	8	73.7	7	61.6	18	224.0	9
UIL	54.8	11	39.0	12	32.3	24	86.0	10	212.0	10
PRU	44.8	25	37.3	14	40.5	15	88.9	8	211.5	11
UDE	54.8	11	37.3	14	30.9	26	82.9	12	205.9	12
SUNY	54.3	13	33.8	19	22.9	40	93.9	3	205.0	13
UCLA	60.4	8	55.1	7	30.8	27	56.7	22	203.1	14
UCSB	49.1	20	44.2	11	41.7	14	58.0	21	193.0	15
NWU	46.5	24	25.9	31	18.3	53	89.0	7	179.6	16
TAM	36.5	37	10.2	62	97.9	3	33.0	38	177.7	17
SYR	61.3	7	36.6	16	39.2	16	40.6	31	177.6	18
UPA	52.2	14	38.6	13	13.2	61	66.4	16	170.3	19
CORN	50.9	17	32.1	21	36.8	19	44.0	29	163.8	20
PSU	30.4	48	15.4	45	30.5	29	86.2	9	162.5	21
UMA	47.0	22	29.9	24	18.7	51	66.8	15	162.3	22
UOK	34.3	43	22.9	35	100.0	1	0.0	83	157.2	23
NCSU	42.6	27	31.7	22	37.7	18	44.2	28	156.3	24
UMI	50.4	19	33.5	20	25.4	34	46.1	27	155.6	25
YALE	51.3	16	48.0	9	19.6	49	36.1	34	155.1	26
UCO	35.2	41	20.0	40	30.5	28	69.2	14	154.8	27
CMU	35.7	40	18.0	41	15.9	56	84.8	11	154.4	28
LEH	50.9	17	34.1	18	33.4	21	28.9	42	147.3	29
OSU	42.2	28	21.1	39	21.7	45	62.3	17	147.3	30
OKSU	20.9	70	7.7	71	98.0	2	19.5	53	146.0	31
UVA	38.3	33	26.7	30	23.7	38	55.9	23	144.6	32
RPI	39.6	30	22.5	36	27.5	30	43.8	30	133.4	33
UWA	49.1	20	29.4	25	22.6	43	26.1	44	127.2	34
UH	21.7	68	9.4	67	38.6	17	55.0	24	124.7	35
PUR	43.5	26	27.4	27	26.2	32	24.6	47	121.6	36
COL	31.7	45	9.8	65	43.1	13	36.3	33	120.9	37
UCD	47.0	22	31.7	23	9.2	69	30.3	39	118.2	38
UTN	7.8	92	1.1	92	86.2	5	14.4	60	109.5	39
LSU	29.6	52	13.2	52	32.8	23	29.5	41	105.1	40

Average of Intensive Composite Scores for all Universities 130.66

TABLE 8

Example of Rank Order of ChE Graduate Programs using a Single, Composite Extensive/Intensive Criterion

University	Composite Score Rescaled[a]	Composite Score Normalized	Deviation[b]	Rank
University of Minnesota	533.9	100.0	4.9	1
Massachusetts Inst. of Technology	515.8	96.6	2.1	2
University of Texas at Austin	453.8	85.0	2.2	3
University of California-Berkeley	319.4	59.8	18.8	4 [c]
University of Wisconsin-Madison	283.5	53.1	8.2	5
University of Delaware	269.8	50.5	6.7	6
Stanford University	267.3	50.1	9.9	7
California Institute of Technology	246.9	46.2	7.3	8
Princeton University	227.4	42.6	6.6	9
Texas A&M University	226.4	42.4	20.4	10 [d]
Univ. of California-Los Angeles	225.6	42.3	15.2	11
Univ. of California-Santa Barbara	219.3	41.1	4.6	12
Univ. of Illinois, Urbana-Champaign	210.0	39.3	8.1	13
Case Western Reserve University	205.5	38.5	14.5	14
Pennsylvania State University	205.1	38.4	15.2	15
Northwestrn University	203.1	38.0	15.8	16
Johns Hopkins University	202.7	38.0	16.4	17
North Carolina State University	196.4	36.8	7.0	18
State Univ. of New York-Buffalo	195.3	36.6	15.2	19
University of Michigan	185.9	34.8	7.5	20
Cornell University	183.0	34.3	6.8	21
University of Pennsylvania	182.4	34.2	20.9	22 [c]
Lehigh University	172.5	32.3	11.9	23
Carnegie Mellon University	171.7	32.2	16.7	24
Purdue University	168.5	31.6	13.3	25
Univ. of Massachusetts, Amherst	167.6	31.4	13.8	26
University of Colorado	159.9	29.9	10.1	27
University of Oklahoma	157.7	29.5	30.4	28 [d]
Syracuse University	151.4	28.4	14.2	29
Ohio State University	146.6	27.5	10.9	30
University of Washington	142.2	26.6	12.8	31
University of California-Davis	137.1	25.7	18.1	32
University of Houston	136.2	25.5	21.6	33
Rensselaer Polytechnic Institute	136.0	25.5	2.9	34
University of Tennessee-Knoxville	134.6	25.2	37.7	35 [d]
University of Virginia	134.5	25.2	7.5	36
Georgia Institute of Technology	134.1	25.1	16.4	37
Louisiana State University	132.5	24.8	13.3	38
Oklahoma State University	131.0	24.5	31.0	39 [d]
Yale University	125.8	23.6	18.1	40

[a] *Extensive score plus rescaled intensive score as described in text.*
[b] *Standard deviation of the rank order numbers of the eight quality measures as described in text.*
[c] *Ranking may be low because of different basis or error in Research Support category.*
[d] *Ranking may be high because of different basis or error in Research Support category.*

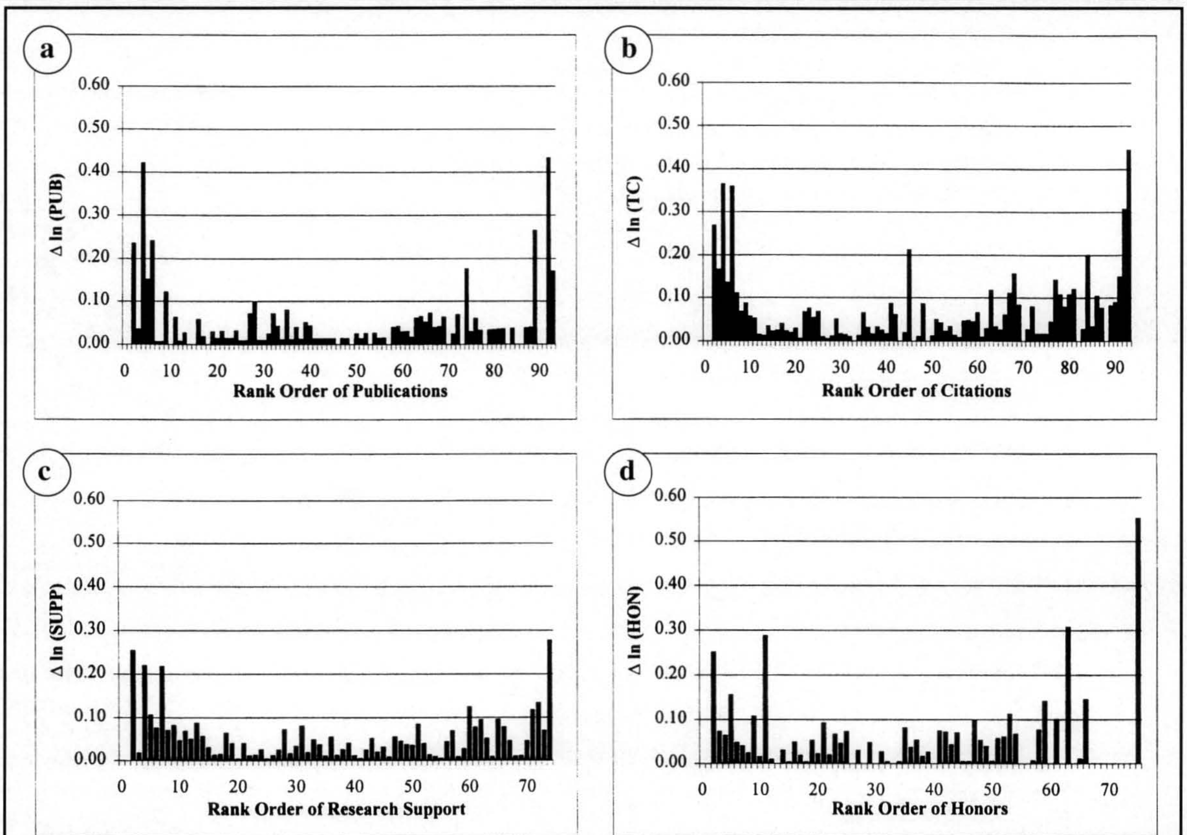

Figure 3. (a) *Fractional change in citations, Δ(TC)/(TC), versus rank order; top-ranked programs are on left.* ***(b)*** *Fractional change in publications, Δ(PUB)/(PUB), versus rank order; top-ranked programs are on left.* ***(c)*** *Fractional change in research support, Δ(SUPP)/(SUPP), versus rank order; top-ranked programs are on left.* ***(d)*** *Fractional change in honors, Δ(HON)/(HON), versus rank order; top-ranked progams are on left.*

into the first decile or out of the tenth decile.

Without knowing details of the data collection, it is not possible to make a rigorous assessment of the uncertainty in the rank ordering. However, a heuristic assessment can be made. We assume, based on experience and for purposes of argument, that there are independent errors of 10% in each of the four extensive numerical data sets: Publications, Citations, Support, and Honors. In the middle range of each of the extensive data sets, the fractional change, $\Delta X/X$, required to move one place in the rank order is approximately 0.03 (see Figure 3). A fractional error of 0.10 therefore corresponds to approximately $0.10/0.03 \approx 3$ places in the rank ordering. Also, if the errors are independent, one would expect an error in the composite rank ordering of extensive criteria to be approximately $\sqrt{4}(3) = 6$ places. If similar arguments are used for the four intensive data sets, we also find an approximate error of six places. This error is not independent of the error in the extensive rank ordering. We conclude that, in the middle range, programs within 5 to 10 places on the composite extensive/intensive rank ordering are essentially indistinguishable from each other. This estimate is consistent with our common-sense interpretation of the rank ordering, *e.g.*, programs in the second decile are probably superior to programs in the third decile, and so on.

The eight separate (though not completely independent) measures of quality give the rankings a certain degree of robustness that a single criterion would not have. The internal consistency of the eight measures of quality is estimated by computing the standard deviation of the rank order number of the eight separate quality categories for each program (see Table 8). For example, for MIT the average of the eight rank orders is 3.5 and the standard deviation of rank orders is just

$$\left\{\frac{(2-3.5)^2+(3-3.5)^2+\cdots}{8-1}\right\}^{1/2} = 2.07$$

Large values of the deviations indicate programs where indi-

TABLE 9
Summary of R^2 Values for Linear Fits Between Rank Order of Faculty Quality (93Q) and Rank Order in the Individual Rankings

Ranking Category	Fit	R^2
PUB	y = mx + b	0.7469
PUB/FAC	y = mx + b	0.6005
CIT	y = mx + b	0.7482
CIT/FAC	y = mx + b	0.6028
SUPP	y = mx + b	0.2484
SUPP/FAC	y = mx + b	0.1351
HON	y = mx + b	0.6993
HON/FAC	y = mx + b	0.6370

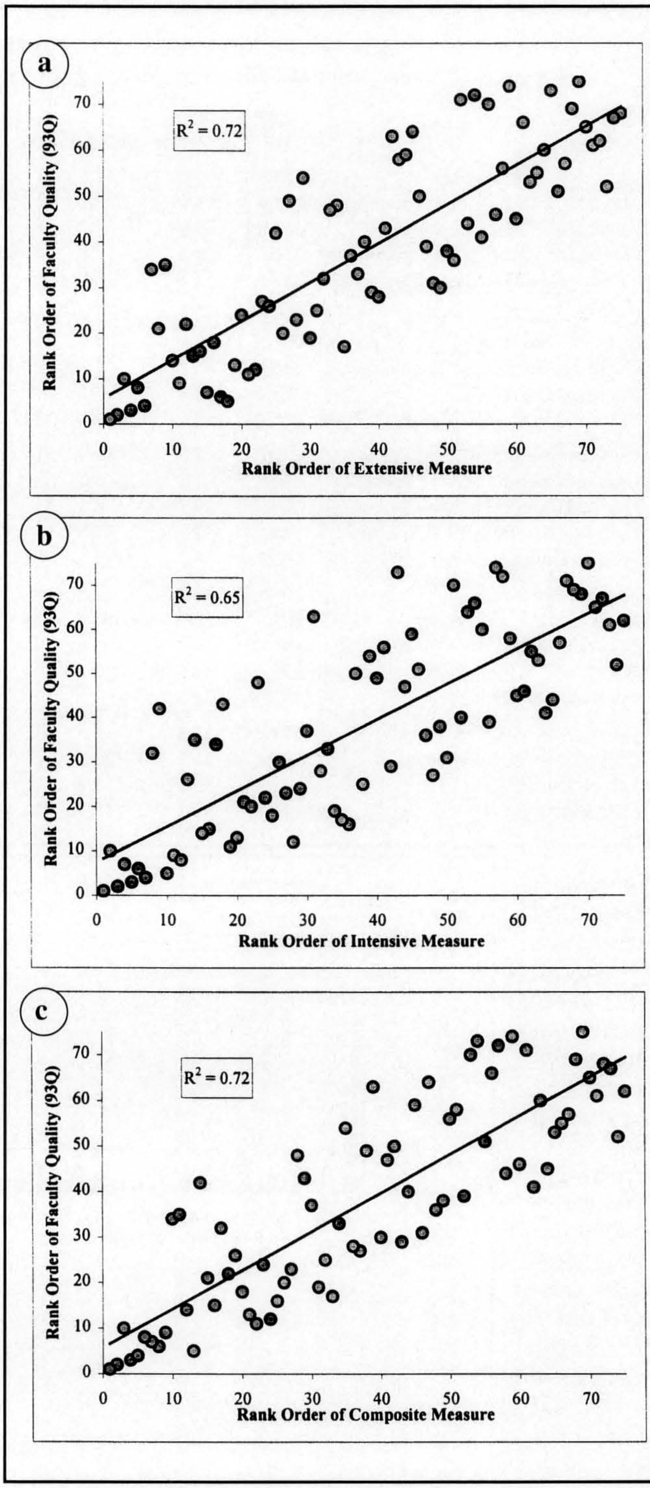

Figure 4. (a) *Composite extensive rank order versus rank order of faculty quality (93Q); top-ranked programs are near origin. R^2=0.72 for linear fit, y=mx+b.* ***(b)*** *Composite intensive rank order versus rank order of faculty quality (93Q); top-ranked programs are near origin. R^2=0.65 for linear fit, y=mx+b.* ***(c)*** *Composite intensive/extensive rank order versus rank order of faculty quality (93Q); top-ranked programs are near origin. R^2=0.72 for linear fit, y=mx+b*

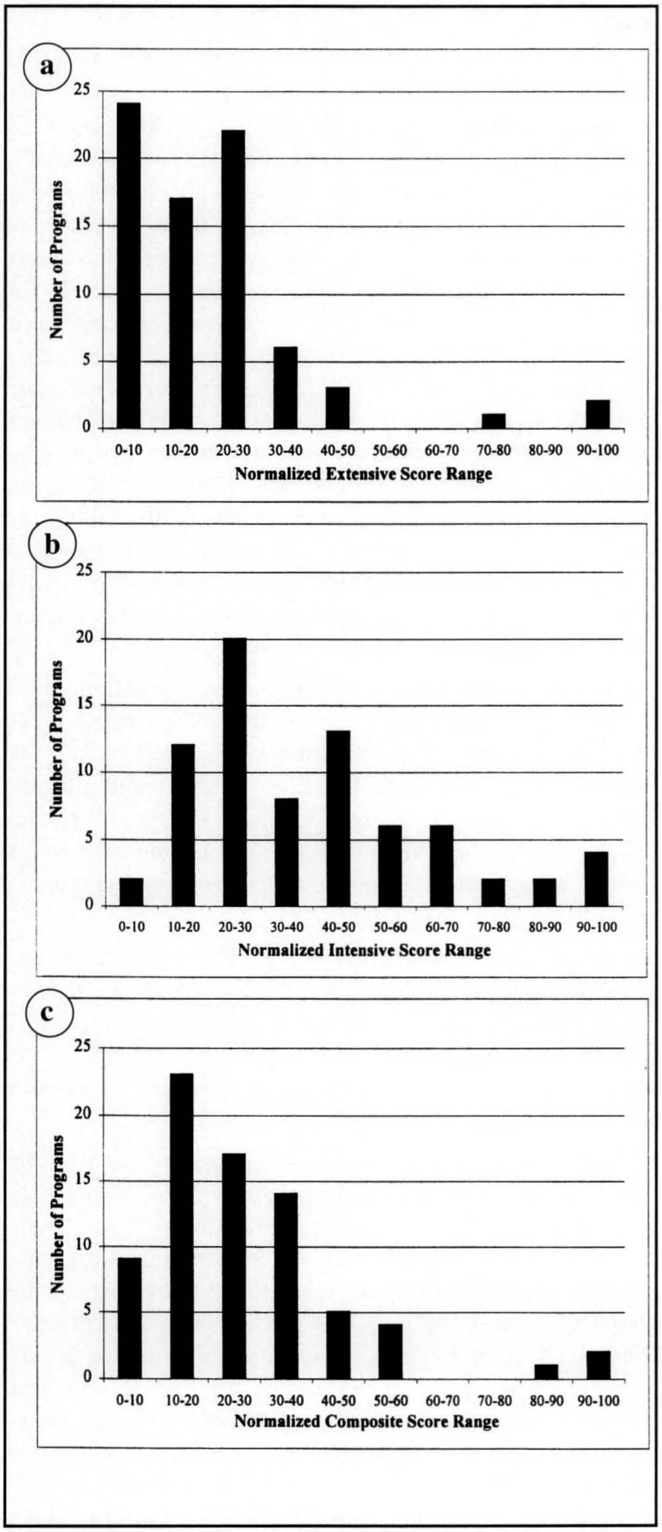

Figure 5. (a) *Histogram showing number of programs versus scaled total extensive score; top-ranked programs are at the right.* ***(b)*** *Histogram showing number of programs versus scaled total intensive score; top-ranked programs are at the right.* ***(c)*** *Histogram showing number of programs versus scaled total composite extensive/intensive score; top-ranked programs are at the right.*

vidual quality rankings are the least internally consistent. In many cases, large deviations are associated with small programs that rank higher in intensive than in extensive categories. However, in some cases, large deviations may indicate problems in the data. For example, four programs have much higher rankings in research support than in the other quality categories: Texas A&M, Oklahoma State University, the University of Oklahoma, and the University of Tennessee. On the other hand, the University of California at Berkeley and the University of Pennsylvania have much lower rankings in research support than they have in the other categories. We believe that these disparities likely arise from different reporting bases and may not reflect true differences in research support. Three programs have a much higher ranking in Honors than in the other quality categories: Pennsylvania State University, Carnegie Mellon University, and Northwestern University.

The rank order of perceived faculty quality (93Q) was correlated with the rank order of each of the separate quality categories (see Table 9). The weakest correlations were found with the two support categories, SUPP and SUPP/TF, consistent with our belief that some of these data are not reported on a consistent basis. Nevertheless, we are reluctant to exclude research support from the quality measures. Research support is probably a better current and leading indicator of quality than the other categories. Also, total research support is a primary criterion used for assessing quality of research universities.[5] Rather than re-ranking the programs excluding SUPP and SUPP/TF, we believe it is more reasonable to identify programs where different bases for reporting support may have strongly influenced the rankings.

Plots of the rank order from the faculty quality survey (93Q) from the NRC report versus the overall extensive, overall intensive, and composite rankings are given in Figure 4. In the figure, the high-quality programs are near the origin. The figure clearly shows how the quality survey and our methods identify the same several programs as the highest quality.

PART 3
DISCUSSION AND RECOMMENDATIONS

Interpretation of Rankings • There is no calibration standard for quality against which any methodology can be tested. Nevertheless, we find it very suggestive that our composite extensive/intensive ranking and the NRC reputational survey identify the same few top programs. For example, comparison of Tables 4 and 8 shows that the same top two programs, MIT and Minnesota, and nine out of the ten top-ranked programs are the same in both the NRC reputational ranking and our numerical ranking. But only three out of ten programs in the second decile and two of ten in the third decile are the same. The NRC reputational rankings, which rely heavily on anecdotal, word-of-mouth information, will be most accurate for the few, high-profile, extremely good programs, and will be less accurate for smaller, lower-profile, and second-tier institutions. But the numerical measures of quality should remain useful in assessing the relative quality of all institutions. *We conclude, subject to the caveats given about the accuracy of the data itself, that our simple numerical measures do correlate with program quality as it is normally understood.*

Further comparison of Tables 4 and 8 leads to additional insights. One may divide programs into three broad categories. First are the programs that are highly rated on both the NRC reputational survey and the numerical ranking. Prime examples are the University of Minnesota, Massachusetts Institute of Technology, the University of Wisconsin, the University of California at Berkeley, and Stanford University. Second are programs that rank significantly higher in the numerical ranking than in the survey. These programs are often (but not always) associated with smaller, research-intensive programs. Examples are the University of California at Los Angeles, Case Western Reserve University, and Johns Hopkins University. Finally, there are well-known programs, which do well in the reputational ranking, that do not do as well in the numerical measures. These programs may be relying on past, rather than current, performance.

Further insight can be obtained from histograms of the final scores, shown in Figure 5. For ease of interpretation, in the figure the scores from Tables 6, 7, and 8 were scaled to give maximum values of 100. Figure 5a and Table 6 clearly show that three programs (MIT, Minnesota, and Texas) have extensive scores well above all other departments. This disparity is lessened somewhat when the intensive scores are compared (Figure 5b and Table 7). This same uneven distribution of scores is found in Figure 5c, which shows the distribution of composite extensive/intensive scores. The top half of the composite score range contains only seven programs; the remaining programs fall in the lower half. The summary shown in Table 8 and Figure 5 indicates that the highest quality chemical engineering programs are relatively few in number and significantly higher in quality than the rest. Below the top five or six programs there is a wide range of programs with relatively similar quality.

Finally, while we believe that for most programs the rankings given here are an accurate reflection of quality, we emphasize once again that one should be cautious in drawing conclusions from the absolute position in the rankings of a single program.

Limitations of Ranking Systems • Respondents to the NRC questionnaire were asked to rate fifty separate programs. An individual respondent will only have personal, detailed knowledge about a small fraction of these. The resulting reputational rankings will inevitably be influenced by the network of informal contacts and acquaintances of the respondents. This will lead to a bias against smaller programs and will also make the reputational rankings a lagging indicator of program quality.

Another major problem with the NRC report, recognized by the committee, was the lack of data on the performance of graduates from the programs. We were unable to find any direct quantitative measure for assessing the performance of graduates of chemical engineering graduate programs. Since one of the principal goals of a graduate program is the education of the next generation of researchers, this is a serious omission indeed. Personnel departments of major corporate employers of PhD chemical engineers often maintain internal ratings of programs based on the performance of their employees. Perhaps this information can be provided in some suitable blind format to future NRC committees. This is a project that could be addressed by the AIChE and the other engineering societies. Another possible measure of performance is the number of graduates that obtain tenure-track appointments at research universities other than their own.

We suggest that future ranking systems also include some measures of the effectiveness of technology transfer. To partially accomplish this, the Publication category could be expanded to include patents issued to faculty and graduate students. Similarly, Citations could include papers or patents cited within patents. More difficult to count, but very useful, would be the number of new businesses formed as a result of activities within the program.

The quality measures used in the NRC report and in this paper are appropriate for doctoral-level, research-based graduate programs. However, master's-level programs, especially practice-oriented programs, are of growing importance. Future ranking systems should attempt to separately measure the quality of these programs.

The difficulty in accounting for the rapidly changing, interdisciplinary nature of modern engineering is another problem encountered when developing ranking systems. Traditional academic boundaries do not always reflect the realities of engineering practice. The NRC report addressed this problem by ranking "programs" rather than "departments." For chemical engineering, these two categories are usually commensurate, but this may not be the case for chemical engineering programs with strong efforts in biotechnology or advanced materials. Ranking programs with major commitments in these fields can be difficult when the academic administrative units do not correspond to the categories used in the ranking scheme. Very strong, interdisciplinary efforts may not appear in the data set, or conversely, remote extraneous efforts can be included. Obtaining a reliable data set, based on uniform criteria, is a formidable task. The NRC committee had great difficulty in defining program boundaries in modern biology and molecular biology, where the pace of change is particularly great.

Neither the NRC report nor this paper uses any measures of the quality of graduate teaching. The lack of quantitative measures of teaching performance is a continuing, long-term problem.

The very long time between the NRC reports (1982 to 1995) is yet another problem. Waiting more than a decade for an assessment is slow, even by the standards of academia. Some form of continuing assessment, for example on a triennial basis, would be more useful. This would give more timely results and would also permit running averages of several years to average out fluctuations in the data.

Concluding Remarks • With all of these difficulties, one can legitimately ask why bother with rankings at all? We believe that universities will be under ever-increasing pressure to justify tuition rates and the cost of performing research. Whether we like it or not, ranking of academic programs will continue and will likely increase. It is in the profession's interest to see that the rankings are based on rational, measurable criteria. But there is little reason to continue relying on surveys. *Reputational rankings only confirm the obvious about the top few programs, permit declining programs to remain complacent, and fail to recognize increasing quality where it occurs.*

Conclusions and Recommendations

- Alternative, measurable quality indices exist that correlate well with graduate program quality as it is normally understood.
- The professional societies, the National Academy of Engineering, and the National Science Foundation should take the lead in developing these quantitative measures of program quality and appropriate data bases to support these measures.
- Special attention should be paid to developing methods for assessing the performance of students after they receive their graduate degrees; this should include using information from employers of graduates.
- Methods of assessing the effectiveness of technology transfer and impact on industry should be developed.
- Assessments should be made on a more frequent schedule, perhaps triennially.

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BOOK REVIEW: *Alternative Fuels*

Continued from page 39.

The use of geothermal energy is presented in Chapter 9. This topical discussion notes that at depths of about six miles from the earth's surface, the temperature is greater than 100°C. This equates to more energy storage than the total thermal energy in all the nuclear and fossil fuel resources—only solar energy is comparable. Along with scientific and technological updates, the advantages and disadvantages of geothermal energy utilization are outlined; this alternative source of energy will potentially become a larger part of the world's energy consumption in the near future because geothermal energy is both available and economical. In the United States, approximately 3 GW of electric power is produced in 20 power plants from geothermal reservoirs. Geothermal energy also has great potential as a practical provider of heat to local areas.

The overall conversion routes of biomass are described in Chapter 10. They include thermal (combustion, gasification, liquefaction, and pyrolysis), anaerobic digestion, and fermentation to liquid ethanol fuel. The descriptions include 15 process diagrams and several tables of data. A selected amount of cost data is provided for ethanol production from lignocellulose.

Chapter 11 presents a comprehensive overview of relatively recent developments in the generation of energy from municipal solid wastes, including spent tires and polymeric materials. Processes include incineration, anaerobic digestion and landfill gas recovery, pyrolysis, thermal cracking, and partial oxidation via supercritical fluids.

In summary, *Alternative Fuels* superbly achieves its purpose by bringing together a wealth of practical information required for a thorough understanding of those chemical process technologies urgently needed for the development of fuels for future use. Dr. Lee is to be commended for his extraordinary efforts in synthesizing all these facts and systems in a clear and consistent manner. Possibly his next book could focus more on the use of biomass, geothermal, and solid waste resources—three areas that are undergoing rapid development. ❐