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The early history of chemical engineering: a reassessment

CLIVE COHEN*

Very few historians have so far turned their attention to the history of chemical engineering, a discipline which impinges on aspects of industrial life as diverse as the manufacture of consumer goods and the generation of nuclear power. However, a number of practising and retired chemical engineers have produced accounts of the late nineteenth-century beginnings and subsequent development of chemical engineering.[1] Their work has set the scene for more recent papers by two academic historians, Colin Divall and James F. Donnelly.[2] There are two particular issues which are frequently discussed, and about which there is a general consensus in this body of work: the origins of academic chemical engineering, and the ways in which its development in the United States differed from that in Europe. In this paper I shall cast doubt on the now conventional picture of these two aspects of the history of chemical engineering.

When the emergence of chemical engineering is discussed in the British and American literature, authors have invariably emphasized the importance of 'unit operations', a method of engineering analysis in the design of plant for the process industries which proved to be very successful for about fifty years, and only began to be superseded in the early 1960s. The term itself was coined in Boston, Massachusetts, in 1915, a fact which suggests that, although with hindsight it was an important element in the differentiation

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1 See, for example, N. R. Amundson, 'P. V. Danckwerts: his research career and its significance', *Chemical Engineering Science* (1986), **41**, 1947–55; F. J. van Antwerpen, 'The origins of chemical engineering', in *History of Chemical Engineering* (ed. W. F. Furter), Washington, 1980, 1–14, and D. C. Freshwater, 'George E. Davis, Norman Swindin, and the empirical tradition in chemical engineering', in Furter, ibid., 97–111; O. A. Hougen, 'Seven decades of chemical engineering', *Chemical Engineering Progress* (1977), **57**, 89; R. Landau, 'Academic–industrial interaction in the early development of chemical engineering at MIT', *Advances in Chemical Engineering* (1991), **16**, 41; L. E. Scriven, 'On the emergence and evolution of chemical engineering', *Advances in Chemical Engineering* (1991), **16**, 3.

2 C. Divall, 'A measure of agreement: employers and engineering studies in the universities of England and Wales, 1897–1939', *Social Studies of Science* (1990), **20**, 65–112, and 'Education for design and production: professional organization, employers and the study of chemical engineering in British universities, 1922–1976', *Technology and Culture* (1994), **35**, 258–88; J. F. Donnelly, 'Representations of applied science: academics and chemical industry in late nineteenth-century England', *Social Studies of Science* (1986), **16**, 195–234, and 'Chemical engineering in England, 1880–1922', *Annals of Science* (1988), **45**, 555–90.

of chemical engineering from other disciplines, unit operations did not play a role at the very beginning of chemical engineering, which was taught at university level from the 1880s. So important does unit operations now seem to be (both to chemical engineers and historians) that many authors seek it in the very early history of chemical engineering. This is often achieved by tracing the *concept* of unit operations back to George Davis, an English consultant who described himself as a chemical engineer, and especially to a one-off series of lectures given by him in Manchester in 1887.[3] However, the same authors are often at pains to point out that chemical engineering emerged first in the United States and only later in Europe. If we are to believe these accounts, therefore, we must accept that George Davis invented unit operations, the basis of chemical engineering in the 1880s, that it was then ignored in Britain, but taken up twenty years later in the United States before being re-exported back to Britain. I intend to show in this paper that a more plausible sequence of events runs as follows: first, university courses called chemical engineering started in the 1880s on both sides of the Atlantic. Secondly, around 1910, an engineering method which came to be called unit operations emerged, again in both the United States and Europe, at substantially the same time. Thirdly, the power of unit operations was enhanced progressively over the following decades by applied research which was carried out in academic institutions and in industry. Fourthly, this led to the growing success of unit operations, and therefore of chemical engineering as a whole, when applied to the design of plant for the process industries after 1920.

The extent to which there is a historiographical consensus among previous writers may be judged from a brief review. In a paper published in 1977, Olaf Hougen, emeritus professor of chemical engineering at the University of Wisconsin (a leading American institution for chemical engineering research), refers to George Davis as an early 'promoter' of chemical engineering, and draws distinctions between the practice of chemical engineering in the United States, Britain and Germany.[4] He reports that in 1880 Davis overheard a chemical manufacturer say 'I have heard of civil engineers, electrical engineers... but never of a chemical engineer'. Hougen, apparently believing this dismissive remark to be symptomatic of the British state of mind at the time, goes on to say that 'as a result of this attitude, the formation of the Institution of Chemical Engineers (United Kingdom) was delayed for 42 years'. In 1979, Klaus Buchholz (described as a technical chemist, researching in biochemical engineering in Frankfurt) suggested that it was the existence of large oil reserves in the United States which led to the development of unit operations there. Buchholz said that this 'signalled a retreat from basic research', in the sense that unit operations was an empirical technique, not entirely based on fundamental

3 S. Gregory ('John Roebuck, 18th century entrepreneur', *Chemical Engineer* (December 1987), No. **443**, 28–31) refers to John Roebuck MD as a member of his 'pantheon of chemical engineers'. Roebuck (1718–94) studied medicine at Edinburgh and Leiden, and later involved himself in business ventures including the volume production of sulphuric acid by the lead chamber process. In the sense that this was a proto-industrial process for chemical production, Gregory may have felt justified in calling it 'chemical engineering', but I think most writers would agree that this would be an anachronistic use of the term. Donnelly (in 'Chemical engineering', op. cit. (2), 557 n6) mentions 'An extremely early reference to the chemical engineer', in 1839, 'in connection with the manufacturer of sulphuric acid, though... the term... was not in general use'.

4 Hougen, op. cit. (1), 92–3.

scientific analysis.[5] Also in 1979, the American Chemical Society organized a symposium on the history of chemical engineering, the proceedings of which were published in the following year under the editorship of William F. Furter.[6] A number of authors repeated the view that chemical engineering emerged first in the United States, although credit for the concept of unit operations was given to Davis, the English consultant. Van Antwerpen, for example, referred to a paper written in 1959 by Warren K. Lewis, who headed the chemical engineering department at the Massachusetts Institute of Technology (MIT) from 1921.[7] Looking back on his part in the preparation of a famous textbook nearly forty years earlier, Lewis (who was 77 years old in 1959) unequivocally credited George Davis with the idea of unit operations.[8] John T. Davies, quoting the same paper by Lewis, accepts that George Davis invented unit operations and that 'in 1901 he systematized this approach in his *Handbook*', but indicates that the topic was 'adopted in the United States much later', and dealt with 'more explicitly' in a chemical engineering course at Battersea Polytechnic, London, in 1914–15.[9] Freshwater also unhesitatingly attributes the origin of unit operations to Davis, although he speculates that we know 'so little... about so important a discovery' partly because of the 'relative unimportance of the... chemical industry in particular in Britain in [Davis's] time'.[10] (One wonders why the largest chemical industry in the world was described by Freshwater, a chemical engineer from Loughborough University, as 'relatively unimportant'.)[11]

Jean-Claude Guédon (of the Institut d'histoire et de sociopolitique des sciences, Université de Montréal, Canada) takes a different view of the emergence of unit operations. He states that by 1925 'Britain had been unable to construct such a notion itself.' The United States, however, had managed this task, and Guédon ascribes this transatlantic contrast to historical differences between education systems and product specialization.[12] This latter point echoes that of Buchholz mentioned above: the implication is that unit operations was a method which was successful in the petroleum and petrochemical industries; the United States had large petroleum reserves; *ergo* the Americans must have developed unit operations. Karl Schoenemann, formerly a professor at the Technische Universität, Darmstadt, writing in 1980, takes a similar view, explaining that 'about 1890... the United States enjoyed a position of organizational superiority because they recognized the importance of chemical engineering as an independent discipline', whereas

5 K. Buchholz, '*Verfahrenstechnik* (Chemical Engineering) – its development, present state and structure', *Social Studies of Science* (1979), **9**, 42 and 54.

6 W. F. Furter (ed.), *History of Chemical Engineering*, Washington, 1980.

7 Antwerpen op. cit. (1), 3–4.

8 The seminal textbook was W. H. Walker, W. K. Lewis and W. H. McAdams, *Principles of Chemical Engineering*, New York, 1923. See also W. K. Lewis, 'The evolution of unit operations', *American Institute of Chemical Engineers Symposium Series* (1959), **55**, 1–8.

9 J. T. Davies, 'Chemical engineering: how did it begin and develop?', in Furter, op. cit. (6), 38.

10 Freshwater, op. cit. (1), 99.

11 L. F. Haber, *The Chemical Industry 1900–1930*, London, 1971, 11, says that 'the British chemical industry... in 1900 was probably still the world's largest, measured by the volume of production and the capital invested'. Although the traditional alkali and bleaching powder businesses had declined, fertilizers and coal tar products were growing rapidly.

12 J.-C. Guédon, 'Conceptual and institutional obstacles to the emergence of unit operations in Europe', in Furter, op. cit. (6), 56.

(apparently) the Germans were obsessed with dyestuffs chemistry, and the British struggled with the millstone of their obsolete heavy inorganic chemical industry.[13] Writing in the same anthology, Westwater suggests that 'the specific words "chemical engineering"... were coined by Professor George E. Davis', who would no doubt have been delighted by the posthumous call to an unidentified chair.[14]

In 1982, the proceedings of a second symposium held under the auspices of the American Chemical Society (ACS), also edited by Furter, was published as *A Century of Chemical Engineering*.[15] Several papers in this volume contrast the development of chemical engineering in Europe and the United States. Trescott affirms that 'unit operations... was operative... in the U.S. chemical industry around 1900', but she quotes various sources who say that 'this transition... [took] place no earlier than the First World War' in Europe.[16] She attributes the Americans' supposed lead in the field to, among other things, a 'mass market mindset'.[17] More recent writers are scarcely less committed to the familiar themes. In yet another compendium of papers sponsored by the ACS and published in 1989, the editor himself, N. A. Peppas, attributes the term 'chemical engineering' to George Davis, and goes on to describe the developments in fundamental analysis which were pioneered at Minnesota University from 1957, and which ultimately rendered the concept of unit operations obsolete.[18] In 1992, Landau (a well-known chemical engineer) and Rosenberg, summarizing the history of the chemical process industries, reiterate the story of the so-called decline of the British industry in the face of the better-educated Germans and the 'rise of the American industry to international pre-eminence'. The American success was said to be based on a number of factors, including the 'emergence of the distinctly American discipline of chemical engineering', which Landau and Rosenberg say was attributable 'to a quite striking degree... [to]... a single institution: M.I.T.'.[19]

What are the views of our contemporary *historians* on the early history of chemical engineering? In his 1986 paper, Donnelly notes that by far the largest proportion of chemists employed in British industry up to 1880 were engaged on the relatively menial and low-status task of chemical analysis. After that date, 'it was being clearly stated that the conversion of laboratory processes to plant scale was an activity distinct from their discovery and investigation. The former activity was sometimes labelled "chemical engineering".'[20] However, when Donnelly goes on to describe the various unsuccessful

13 K. Schoenemann, 'The separate development of chemical engineering in Germany', in Furter, op. cit. (6), 251.

14 J. W. Westwater, 'The beginnings of chemical engineering education in the USA', in Furter, op. cit. (6), 142.

15 W. F. Furter (ed.), *A Century of Chemical Engineering*, New York, 1982.

16 M. M. Trescott, 'Unit operations in the chemical industry: an American innovation in modern chemical engineering', in Furter, op. cit. (15), 9.

17 Trescott, op. cit. (16), 10.

18 N. A. Peppas, 'The origins of chemical engineering', in *One Hundred Years of Chemical Engineering* (ed. N. A. Peppas), Dordrecht, 1989, 3–12.

19 R. Landau and N. Rosenberg, 'Successful commercialization in the chemical process industries', in *Technology and the Wealth of Nations* (ed. N. Rosenberg, R. Landau and D. C. Mowery), Stanford, 1992, 81 and 85.

20 Donnelly, 'Representations', op. cit. (2), 210.

attempts, from the mid-1880s to the end of the century, by British academics to establish degree courses in applied chemistry, chemical technology or even chemical engineering, it is clear that, if George Davis had indeed sown the seed of chemical engineering in 1887, it had not immediately germinated. In a later paper, Donnelly deals in more detail with the early British courses in chemical engineering. He links the concept later called 'unit operations' with Davis's presentation of his services as a consultant. However, although he portrays a more credible picture than many other writers of the origin and differentiation of chemical engineering as an independent discipline, he nevertheless describes it as 'both numerically small and placed in an institutionally and ideologically derivative relationship to chemistry' in England, whereas he accepts 'the greater importance of chemical engineering in U.S.A.'.[21] Colin Divall is as convinced as Donnelly that chemical engineering grew far more successfully in the United States than in Britain up to the Second World War.[22]

It is reasonable to conclude then, that previous authors are generally satisfied that chemical engineering developed in the United States, although the fundamental concept behind it was probably the brainchild of George Davis. I shall show here that these views are at best an oversimplification of the history of chemical engineering.

THE ORIGINS OF CHEMICAL ENGINEERING EDUCATION IN LONDON AND BOSTON

George E. Davis was one of the earliest consultants to call himself a chemical engineer and actively to promote chemical engineering as a distinct subject for study. After taking chemistry at the Slough Mechanics' Institute and at the Royal School of Mines, Davis joined Bealey's Bleach Works in Manchester at the age of 20.[23] He subsequently worked for a succession of chemical firms, and later gained some years' experience as a consultant. He was appointed to the Alkali Inspectorate in 1881, with responsibility in the English Midlands for policing the toxic emissions of the Leblanc soda ash factories.[24] At about this time, Davis took over as secretary of a new manufacturers' association, the Society of Chemical Industry, for which in 1880 he had unsuccessfully canvassed the name 'Society of Chemical Engineers'.[25] By 1884, Davis was again in private practice in Manchester, having resigned from the Inspectorate the year before. Three years later, he gave his famous series of lectures at Manchester Technical School.[26] This course was not repeated, but the lectures were reprinted in 1888 in the *Chemical Trade Journal*, a publication run by Davis and his brother. Davis's lecture course 'resembled a plant manufacturer's catalogue', and, indeed, it seems that 'consultant engineers frequently did not design machinery so much

21 Donnelly, 'Chemical engineering', op. cit. (2), 587–8.
22 Divall, 'Education', op. cit. (2), 264.
23 Freshwater, op. cit. (1), 98.
24 Donnelly, 'Chemical engineering', op. cit. (2), 561.
25 Donnelly, 'Chemical engineering', op. cit. (2), 557.
26 Donnelly, 'Chemical engineering', op. cit. (2), 561.

as select and combine that of specialist equipment manufacturers'.[27] Items of plant such as boilers or heat exchangers were essentially the same, whether they were used in tar distillation or nitrogen fixation. Manufacturers' catalogues described these and other items and indicated the various applications for which they could be used. Early 'chemical engineers' selected from such catalogues the pieces of plant which they believed would best meet their clients' needs. In 1901, Davis published *A Handbook of Chemical Engineering*, a textbook based on his lectures of 1887.[28] Though purely descriptive, the *Handbook* included chapters on 'The fitting of a technical laboratory', 'Materials used in plant construction', 'Production and supply of steam' as well as (in volume 2, published a year later) chapters on 'Separating solubles from insolubles', 'Evaporation and distillation', and so on. It is this latter group of chapters which has led writers to attribute to Davis the concept of 'unit operations'.

Three years before George Davis's allegedly seminal series of lectures, the first university-level course called chemical engineering was actually announced by the Central Institution, a new college financed by the Livery Companies of London and located in Exhibition Road, South Kensington. The purpose of the Central Institution was to train students to become:

1. Technical teachers.
2. Mechanical, civil, and electrical engineers, architects, builders, and decorative artists.
3. Principals, superintendants, and managers of chemical and other manufacturing works.[29]

At the Council meeting of the City and Guilds of London Institute in February 1884, it was resolved that four professors should immediately be recruited for the Central, to head the departments of Chemistry, Engineering, Mechanics & Mathematics, and Physics. The inclusion of a department of chemistry in what was essentially an engineering college was consistent with the City and Guilds Institute's desire to create a curriculum for trainee managers in the chemical industry. Bud and Roberts have pointed out that courses in chemistry were widespread and popular from the 1840s, and that the initial emphasis on state support for scientific (often mainly chemical) education for the artisan, gave way by 1870 to the encouragement of this training for 'the teacher, the manager and the proprietor'.[30]

27 Donnelly, 'Chemical engineering', op. cit. (2), 563 and 566. See also J. C. Shears, *Machinery and Apparatus for Manufacturing Chemists*, London, 1895 (available in the Science Museum Library, South Kensington), which predates Davis's textbook by six years. It gives advice on the location and construction of a chemical factory, and describes equipment suitable for various operations. Such books were presumably used by consultants and manufacturers, and could indeed be compiled from plant manufacturers' catalogues.

28 G. E. Davis, *A Handbook of Chemical Engineering*, 2 vols., Manchester, 1901, is available at the library of the Institution of Chemical Engineers, Rugby. See also Freshwater, op. cit. (1), 101.

29 See Imperial College Archive, *A Short Notice... The Opening... Of The Central Institution*, London, 25 June 1884, 18. Item 3 above clearly indicates the importance of the chemical industry in the minds of the founding fathers of the Central Institution, though when the *Preliminary Programme* of the Central was published two months later, in August 1884, the reference to 'chemical works' had been dropped.

30 R. Bud and G. K. Roberts, *Science versus Practice: Chemistry in Victorian Britain*, Manchester, 1984, ch. 3, and 135.

Henry E. Armstrong was appointed to the chair of chemistry at the Central.[31] Given the practical aims of the governing body of the Central, they had hoped to appoint a professor with industrial experience, but none was available. For the first four years of its existence, the degree course in Armstrong's department was called 'Chemical Engineering', and it led to the 'Diploma of Chemical Engineer' (*sic*).[32] But after 1888–89 the title 'Chemical Engineering' was dropped and the curriculum offered by Armstrong was simply referred to as the 'Chemical Department'.[33] The course programme for 1885 shows that the first-year timetable in Armstrong's department included classes in mathematics, physics, chemistry, engineering and German. In the second year, German and physics were dropped, and while lectures in mathematics, chemistry and engineering continued, much more time was devoted to laboratory work in chemistry and engineering. In the third year, candidates for the diploma in chemical engineering were required to do more analytical and applied chemistry, and to 'devote attention to physical-chemical methods of enquiry'.[34]

Donnelly has suggested that Henry Armstrong was not the right man for the job at the Central Institution, pointing to evidence of conflict between Armstrong's inclination to teach a pure chemistry course and desire to carry out research in chemistry on the one hand, and the wish of Central's Board of Studies to offer an industrially orientated course on the other.[35] He portrays Armstrong's course as a hodgepodge of subjects imposed on him by Central's authorities, with whom he was often at loggerheads. Donnelly also implies that the course title 'Chemical Engineering' was dropped because of Armstrong's preference for science.[36] It is possible, however, that the authorities changed the name as part of their efforts to compete with the more popular chemistry course available at the nearby Royal College of Science. Armstrong's view of himself as 'a curricular innovator with an orientation towards scientific method' was rejected by Donnelly, but he may have been hasty to do so. There is no reason in principle why chemical engineering could not have emerged from a scientific approach to industrial chemistry, in which the design of chemical plant would be based on a fundamental scientific analysis of the chemical and physical processes involved. It is quite likely that Armstrong would believe so; certainly

31 Armstrong had studied at the Royal College of Chemistry (later the Royal College of Science) and was awarded his Ph.D. in Leipzig in 1870, when he was twenty-two years old. Six years later, he was elected Fellow of the Royal Society. See Imperial College Archive, 'Armstrong Papers Second Series', London, 1974, 3.

32 Annual Calendars are available in the Imperial College Archive. From 1885, when the Central Institution opened, these Calendars were called the *Programme of the Central Institution* (hereafter *Programme*) and from 1907, when the Central was absorbed into Imperial College, they are called the *Calendar of Imperial College* (hereafter *Calendar*). The diploma of 'Chemical Engineer' is mentioned on p. 25 of the *Programme* dated 1885.

33 See *Programme*, op. cit. (32), 1888/89, 16, and 1889/90, 19. The numbers of full-time students attracted to Armstrong's course were always disappointing: see J. V. Eyre, *Henry Edward Armstrong 1848–1937*, London, 1958, 111. Soon, its main function became the teaching of chemistry to mechanical and electrical engineers. Armstrong saw it as his mission to teach the scientific method to engineers via his experimental chemistry course: see H. E. Armstrong, 'The teaching of scientific method', in *Educational Times*, London, May 1891, 1–16, available in the Imperial College Archive, 'Armstrong Papers', op. cit. (31).

34 *Programme*, op. cit. (32), 1885/86, 25–6.

35 Donnelly, 'Chemical engineering', op. cit. (2), 558–61.

36 Donnelly, 'Representations', op. cit. (2), 218, and 'Chemical engineering', op. cit. (2), 559.

this belief in the scientific basis of technology was held by some eminent American contemporaries.[37] He believed that all students would benefit from a thorough grounding in scientific method: this was his great 'curricular innovation'. In the event, it did not prove to be the catalyst which accelerated the growth of the new discipline of chemical engineering – that role was played around 1910 by unit operations, which as we shall see was 'engineering-science', rather than pure science. It is clear that although Armstrong's course was in existence there was not yet a defined and generally acknowledged discipline of chemical engineering, indeed, only a few consultants to the chemical industry were calling themselves chemical engineers. Employers would not necessarily have been prepared to accept such hybrid trainees as the Central Institution was offering, preferring instead to use a combination of chemists and mechanical engineers, or to train chemistry graduates on the job in the engineering aspects of their specific businesses. Therefore, although Armstrong's course lasted for over twenty-five years, it ultimately failed simply because its graduates (despite the fact that a number did become eminent academics or industrialists) were not especially attractive to employers.[38] Until chemical engineers had some special expertise which other graduates could not offer, courses in chemical engineering were unlikely to be successful. This view is confirmed by the fact that other attempts to establish undergraduate courses in technology for the chemical industry at Owen's College, Manchester, and at University College London, did not survive the 1880s, and also by what happened in the first few years of a similar chemical engineering course at Boston Tech.[39]

After Imperial College was formed in 1907, the chemistry classes of Armstrong's course were transferred to the Royal College of Science's chemistry department, and four years later Armstrong's department in the City and Guilds College was closed.[40] But even before that, the chemistry department of the Royal College of Science had begun to set up a sub-department of chemical technology which offered postgraduate instruction in (among other things) chemical engineering.[41] The first step had been the appointment in 1910 of John W. Hinchley as part-time lecturer to teach 'the design of plant required for chemical engineering' to chemists. The following year the head of the chemistry department offered some temporary space to the fledgling department of chemical technology, and full-time staff were appointed.[42] Professor William A. Bone (whose main interest was fuel technology) was recruited from Leeds as head of chemical technology. Hinchley's course on chemical engineering was transferred to Bone's department when it opened in 1912,

37 In John W. Servos, *Physical Chemistry from Ostwald to Pauling*, Stanford, 1990, 266, Servos states that George E. Hale, Arthur A. Noyes and Robert A. Millikan (early leading figures at the California Institute of Technology) 'were true believers in the notion that basic science had strong and direct links with technology'.

38 K. E. Weale, *City and Guilds College: A Centenary History*, London, 1985, 14.

39 Donnelly, 'Representations', op. cit. (2), 216–17; Massachusetts Institute of Technology was known as Boston Tech until 1916, when the local patronage of the 'Boston aristocracy' gave way to the multi-million dollar support of George Eastman, the DuPont cousins and others, and the college moved across the Charles river to Cambridge. See J. W. Servos, 'The industrial relations of science: chemistry at MIT, 1900–1939', *Isis* (1980), **71**, 532 and 538; and D. F. Noble, *America by Design*, New York, 1977, 141.

40 Imperial College was formed by uniting three constituent colleges: City and Guilds College (engineering; formerly the Central Institution), the Royal College of Science and the Royal School of Mines.

41 *Calendar*, op. cit. (32), 1913/14, 66.

42 Weale, op. cit. (38), 31–2.

offering a two-year postgraduate course. Most of the students were graduates of the chemistry department. From the beginning, the department of chemical technology had a strong industrial orientation. Hinchley, who had introduced his course at Battersea Polytechnic in 1909, now taught chemical engineering for two days a week at Imperial College. A generation younger than George Davis and Henry Armstrong, Hinchley had first worked in engineering, before graduating from the Royal School of Mines in metallurgy. He worked in Dublin on colour photography, and in Bangkok as technical head of the Siamese mint, returning to London to practise as a consultant in the design of chemical plant.[43] It is clear from the description in the *Calendar* of Imperial College that Hinchley's course embraces the concept of unit operations.[44] By 1919, the topic 'Designs of simple units of plant' appears under the section of the curriculum headed 'Drawing Office and Laboratory Work'.[45] It seems likely that Hinchley, in adopting this unit operations approach to the teaching of chemical engineering, was aware of George Davis's *Handbook* of 1901, or the revised and expanded version prepared largely by Davis's only pupil, Norman Swindin, in 1904.[46] However, that does not imply a causal link between Davis's book and Hinchley's course. Davis had been a consultant to the chemical trade who realized that he could offer substantially the same advice to different (and possibly competing) commercial clients by recommending items of plant suitable for carrying out various operations, whereas over twenty years later, Hinchley and others were beginning to tackle the engineering analysis of the performance of units of plant; that is, to generate the engineering knowledge which would eventually have a wide application to the design of chemical installations.

Before exploring this point, it is interesting to note the complex evolution of Hinchley's course at Imperial College. Initially, it was called 'chemical engineering' and it formed simply one part of the postgraduate programme in chemical technology. In 1913, it represented 20 per cent of the lectures given in the first year. It dealt with the economic evaluation of industrial projects, the specification of plant (including materials of construction), heat transfer calculations, and unit operations.[47] By 1930, while general course headings were similar, the treatment of heat transfer had become much more scientific, in line with the important American textbook of Walker, Lewis and McAdams, published in 1923.[48] The second year (previously devoted to project work) had been filled with lectures, including a course on thermodynamics. Also in that year, it was announced that research facilities 'will be arranged when convenient'. In 1938, when the undergraduate course was offered for the first time, and the department moved from the Royal College of Science to the City and Guilds College, where the other engineering disciplines were located, chemical engineering was still only a part of the curriculum offered by the department of chemical technology, the other parts being technology of fuel, flame and combustion, high pressure reactions, chemical thermodynamics, and refractory

43 Weale, op. cit. (38), 33.
44 *Calendar*, op. cit. (32), 1911/12, 27–8.
45 *Calendar*, op. cit. (32), 1919/20, 155.
46 Freshwater, op. cit. (1), 104.
47 *Calendar*, op. cit. (32), 1913/14, 32.
48 See Walker *et al.*, op. cit. (8).

materials and silicate technology. Twenty-six separate research topics, some of them unit operations, were said to be current. By 1945, the name of the department had been changed to 'Chemical Engineering and Applied Chemistry'. Research work had expanded considerably; 'chemical engineering' was one of the topics. In 1950, the term 'chemical engineering' in the context of research projects referred to unit operations, but by 1955, the entire department was called simply 'Chemical Engineering', and the research groups included 'Chemical Engineering Operations'. Chemical engineering, it seems, had finally won its battle to become the generic name for what was being taught in the department, and now *included* combustion, high-pressure technology, fuel technology, applied chemical kinetics and thermodynamics, as well as its old bailiwick, unit operations. Chemical engineering at Imperial College had originally been part of chemical technology, but now the opposite was the case. There was a slight relapse from this position, because five years later the department's name was again changed, this time to 'Chemical Engineering and Chemical Technology'. By 1965, unit operations had disappeared from the Imperial College *Calendar*, being replaced in the list of research groups by 'Transport Processes', indicating that scientific fundamentals had taken over from the empirical approximations of unit operations, in which complete pieces of plant had been treated as units of study.

Returning to the nature of Hinchley's early course, the increasing impact of the engineering-science approach of unit operations can clearly be seen from the Imperial College *Calendars*. For example, the exchange of heat between fluids in chemical plant is of fundamental importance, and it is instructive to follow the changing nature of heat transfer studies over the decade from 1911. In the Imperial College *Calendar* for 1911/12, we find in the description of Hinchley's course:

> The design of plants for evaporation; (a) by direct fire; (b) by the circulation of hot fluids... Calculations involved in the design of distilling cooling and condensing plants.

By 1913/14, we see:

> Heat transference calculations. The value of graphical methods of solving practical problems.

In the 1919/20 *Calendar* (still describing Hinchley's course) we find:

> Estimation of the rate of transfer of heat through materials and surfaces. Co-efficients of heat transfer through metallic diaphragms from gas to liquids, steam to liquids, liquids to liquids, etc. Heat insulation. Calculation of heat losses through composite diaphragms.

The language of this last quotation is very close to 1950s terminology. I see in these quotations an evolution from relatively rudimentary design work based on limited experience and data, towards a situation where scientific analysis is combined with experimental data (the latter were required, for example, in determining heat transfer coefficients). I am convinced that Hinchley was working on an altogether different level from Davis who, a generation earlier, had described in a merely qualitative way the appropriate uses of the various units of plant available to the chemical manufacturer.

The earliest undergraduate course in the United States to be given the title 'chemical engineering' was proposed by Lewis M. Norton, and first offered in 1888 at Boston Tech. Norton was born in 1855 (seven years after Henry Armstrong), and studied chemistry at Boston before taking his Ph.D. in Göttingen in 1879. On his return to the United States, he spent two years in industry, working for the Amoskeag Manufacturing Company in Manchester, New Hampshire, before returning to Boston to teach organic and industrial chemistry.[49] The chemical engineering course which he inaugurated seven years later is said to have been based on German practice, describing the manufacture of industrial chemicals.[50] It is also said to have 'combined a rather thorough curriculum in mechanical engineering with a fair background in general, theoretical, and applied chemistry'.[51] In short, it was similar to Armstrong's course (which was running contemporaneously at the Central in London) both in content and because it was an industrial chemistry course offered in an engineering college, taught by a German-trained chemist. Norton died suddenly in 1893, and Frank H. Thorp, another chemistry graduate from Boston, recently returned from Germany with a Ph.D. from Heidelberg, was appointed to succeed him. Over the next few years, several more German-trained chemists joined the chemistry department at Boston, including Arthur A. Noyes, William H. Walker and Warren K. Lewis. Walker was recruited in 1902 specifically to reorganize the chemical engineering course which (again, like Armstrong's in London) was not proving to be popular.[52]

Within this young and ambitious academic team in the Boston chemistry department, there emerged in the early years of the twentieth century two schools of thought as to how Boston Tech in general and the chemistry department in particular should develop. Noyes and his supporters believed that the future lay in 'converting Boston Tech from a simple engineering school into a science-based university complete with a graduate school oriented towards basic research'.[53] Leading the other camp was Walker, supported by his former partner Little (in his capacity as an interested Boston Tech alumnus), whose friends held the view that the college should not turn its back on its origins in the teaching of engineering. They did not believe that a detailed knowledge of fundamental science provided solutions to the practical engineering problems encountered in designing and operating a chemical plant. Only a thorough familiarity with industrial problems (such as scaling up, working within cost constraints, being alert to the possible uses of by-products and writing business-orientated reports) would teach the student when and how to apply scientific theory. In Walker's opinion, it was 'a much smaller matter to both teach and learn pure science than...to intelligently apply this science to the solution of problems as they arise in daily life'.[54] The rivalry between the Noyes and Walker factions was intense and their aims irreconcilable. Noyes' influence within the chemistry department (which included chemical engineering until 1921) declined, however, as the popularity of the chemical engineering degree overhauled that of the chemistry course. In the five years to 1909, Boston Tech awarded 65 SBs in chemical engineering and 82 in chemistry. Five years later, the number in chemical engineering had risen to 132, while in chemistry it had fallen to 50.[55] It was therefore in the early years of the twentieth century that chemical

49 G. C. Williams and J. E. Vivian, 'Pioneers in chemical engineering at M.I.T.', in Furter, op. cit. (6), 113.
50 H. C. Weber, 'The improbable achievement: chemical engineering at M.I.T.', in Furter, op. cit. (6), 77.
51 Williams and Vivian, op. cit. (49), 113.
52 Williams and Vivian, op. cit. (49), 116.
53 Servos, op. cit. (39), 533–4.
54 Servos, op. cit. (39), 535.
55 Servos, op. cit. (39), 538.

engineering began to flourish at the expense of chemistry at MIT. This corresponds to the situation at the Central in London, where Armstrong's chemistry-orientated, scientific-method approach was finally abandoned in favour of Hinchley's new unit operations course.[56] The new factor common to chemical engineering curricula in the United States and Europe after 1910, was 'unit operations', a set of techniques (described in more detail in the next section) which relied on applied research and which became increasingly successful as a design tool with which chemical engineers were able to predict the performance of units of plant.

To summarize, I want to make two points about the development of chemical engineering in Britain and the United States: first chemical engineering was indeed taught in universities from the 1880s. Secondly, after two or three decades a difference of opinion within academic chemical engineering (as examples, I have contrasted the views of Armstrong and Hinchley in London, and those of Noyes and Walker in Boston) began to be resolved. Unit operations was a crucial aspect of the resolution of this controversy, which may well have been rooted in earlier discussion between those who believed that industrial performance could best be advanced through 'pure research' based on fundamental science (physics and chemistry) on the one hand, and those who believed that the future lay in 'applied research' (an engineering science approach) on the other.[57] I am not saying that the inclusion of unit operations in the teaching of chemical engineering happened at precisely the same time on both sides of the Atlantic, nor do I maintain that the applied research on which the success of the method depended proceeded at exactly the same pace in London and Boston. I am simply pointing out that academic chemical engineering existed in these two centres before 1890, and that it was not until two or three decades later, when unit operations appeared in their curricula, that these university courses started to become increasingly popular with students and employers.

UNIT OPERATIONS

I have argued above that before the First World War the mixed fortunes of chemical engineering curricula were revitalized (with the help of John Hinchley in London and of William Walker, two years his senior, in Boston) by the inclusion of courses in 'unit operations', which were specific processes (usually involving physical, rather than chemical change) which were common throughout the chemical industry. Examples are heating and cooling of fluids, distillation, crystallization, filtration, pulverization and so forth. In this approach, the design of complete chemical plants could be broken down into the design of linked pieces of equipment, whose performance could be analysed and studied separately. Research work led to improvements to the various units of plant, and the

56 Servos, op. cit. (37), 256, quotes Noyes' views on the education of engineers: they are remarkably similar to those of Armstrong. See Armstrong, op. cit. (33).

57 Bud and Roberts have described the earlier debate between those who advocated the teaching of pure science and pure scientific research as the route to greater industrial achievement, and those who believed that applied science was worthy of academic study in its own right, and that applied research would yield the advances in technology which were required to maintain Britain's industrial leadership. For example, see Bud and Roberts, op. cit. (30), 71, 85–7, 156–7.

collection of data over a range of operating conditions enabled chemical engineers to build up empirical methods of relating performance to the values of parameters such as feed rates, operating temperature and pressures, and the physical characteristics (for example, density, viscosity, specific heat) of the process fluids and the materials from which the equipment was constructed. The study of unit operations proved to be very successful, and led to a significant increase in the ability of the chemical engineer accurately to *design* units of plant, thereby reducing or eliminating the need to build expensive pilot plant.

William Walker introduced unit operations (although not yet called that by name) into the chemical engineering course at Boston Tech in 1905. Walker had graduated from Pennsylvania State University in chemistry and obtained his Ph.D. at Göttingen in 1892. He taught at Pennsylvania for two years before moving to Boston Tech as an instructor in analytical chemistry.[58] In 1900, he left his academic post to join Arthur Little to form Little and Walker, a firm of consulting chemists in Boston. Two years later, Walker returned to teach at Boston Tech. In 1905, he was also appointed to a lectureship in chemical engineering at Harvard. Walker was an accomplished lecturer and a man of strong personality who favourably impressed both academics and industrialists. His success in reorientating the undergraduate course so that it was relevant to the needs of industry derived from his links with Little, and his teaching of the concept of unit operations. It is possible that Walker took this idea from George Davis's *Handbook of Chemical Engineering*, for he is said to have owned an annotated copy, but the motivation to develop unit operations is more likely to have come from his industrial experience, and his long association with Little, whose firm was by 1918 the largest engineering consultancy in the United States.[59] Little took a special interest in the education of chemical engineers, who were in demand among his industrial clients. He was also a tireless promoter of applied research, without which unit operations would have been of small use to the practising chemical engineer.[60] This key point seems to have been ignored by other historians of chemical engineering. A body of engineering knowledge had first to be assembled, necessitating close co-operation between consulting chemical engineers and research workers, who might be in industry or academia. Vincenti, writing about the development of aeronautical engineering, has described how the approach of the engineer to problems of fluid mechanics and thermodynamics differed from that of the physicist.[61] Vincenti points out that the engineer (unlike the physicist) works in 'an environment where cost constraints are central'.[62] Moreover, the engineer must avoid mistakes, which can be very costly in terms of life as well as financially. Vincenti's analysis could as well have applied to unit operations which, like the method (control-volume analysis) he described for solving fluid mechanical problems in aeronautics, was a system devised by consultants who were also teachers. The work quoted by Vincenti was originated for a limited class of physical conditions by Ludwig Prandtl in Göttingen around 1910, and gradually extended

58 Williams and Vivian, op. cit. (49), 115.

59 Scriven, op. cit. (1), 12; Noble, op. cit. (39), 156.

60 T. Reynolds, *75 Years of Progress: A history of the American Institute of Chemical Engineers 1908–1983*, New York, 1983, 12, quotes in full the definition of unit operations in Little's report.

61 W. Vincenti, *What Engineers Know and How They Know It*, Baltimore, 1990, 112–36.

62 Vincenti, op. cit. (61), 132.

to more general conditions at (for example) MIT from the 1930s. There seem to be parallels with unit operations, and it may be, therefore, that unit operations has its roots not in George Davis's descriptive work of the 1880s but in the much later movement towards the practical application of 'engineering science'. The idea that the engineering-science approach to solving chemical engineering problems was gaining ground between 1910 and 1920 is supported by evidence from the Imperial College *Calendars* quoted above.[63]

Around 1920, Walker, Lewis and McAdams co-wrote *Principles of Chemical Engineering*.[64] Unit operations was now systematically organized and, for the first time in a textbook, quantified. The book provided powerful mathematical tools and engineering data which made it possible for chemical engineers in industry routinely to design various units of equipment to meet specific performance requirements. By the early 1920s, unit operations was an important part of the teaching of chemical engineering at MIT and a growing number of other American colleges, as well as at Imperial College, London.[65] In addition to its utility to the practising engineer and the researcher, there are a number of other reasons why unit operations led to a resounding success for the *Principles of Chemical Engineering*, which remained in print in three editions over fifteen years.[66] First, it was a system which the consultant could use throughout the industry without breaking clients' confidences. Secondly, the scientific management movement which began in the late nineteenth century had achieved many improvements in industrial efficiency by analysing work into small units.[67] Industry was receptive to a concept which focused attention on individual pieces of operating plant. Thirdly, the fact that there was a relatively small number of processes called 'unit operations', and that they found practical application in a wide variety of industrial and research situations, meant that the concept was an excellent tool for teaching chemical engineering. Fourthly, unit operations was a device by which practitioners could differentiate themselves from the larger, well-established disciplines (principally chemistry and mechanical engineering). Academics and consultants shared the need to demonstrate that in chemical engineering they offered a new speciality which was uniquely able to satisfy the demands of the chemical industry.

Of these four reasons (in addition to its practical design utility) for the ready acceptance of the unit operations idea, Donnelly stresses only one, the consultants' need for confidentiality.[68] To be sure, the influence wielded by individual consultants could be very considerable. We shall see later that the education committee of the American Institute of Chemical Engineers (AIChE), under the chairmanship of the consultant, Arthur Little, from

63 See p. 180, above.

64 See Walker *et al.*, op. cit. (8). Lewis had been a chemical engineering undergraduate student of Walker's, had obtained a Ph.D. at Breslau in 1911, and returned to teach at MIT, where in 1920 he became head of the department of chemical engineering. The third author of *Principles*, McAdams, received his MS in chemical engineering at MIT in 1917, and returned to join the faculty after war service. See Williams and Vivian, op. cit. (49), 116–18.

65 Hougen, op. cit. (1), 96–8, shows that at the University of Wisconsin-Madison, unit operations entered the curriculum around 1915 and began to be superseded after 1955.

66 Emeritus Professor of chemical engineering (Imperial College), R. W. H. Sargent used a late edition of the *Principles* as a textbook after the Second World War (personal communication).

67 See, for example, Noble, op. cit. (39), 266–76.

68 Donnelly, 'Chemical engineering', op. cit. (2), 587.

1919, put unit operations at the heart of the accreditation system under which university courses in the United States became more uniform in the late 1920s. Moreover John Hinchley (whose course at Imperial College from 1910 included unit operations, though not at first called so by name) acted as a consultant to ten firms as late as 1923.[69] Therefore, I acknowledge (with Donnelly) the role played by consultants in the growing importance of unit operations in the 1910s. But the other reasons which I have listed above (compatibility with the new industrial management techniques, ease of teaching and learning, and professional differentiation, but most of all its utility as a design tool) reinforced still further the success of unit operations which continued as a research topic in Britain and the United States until the 1960s. Donnelly states that unit operations was 'characteristic of academic chemical engineering', implying that it was crucial to the existence of chemical engineering as a discipline, whereas I have argued here that chemical engineering existed long before unit operations. In order to justify the centrality of unit operations, Donnelly has to trace the concept back to one of the earliest known self-styled chemical engineers, George Davis, whereas I have put forward the argument that unit operations could not have existed until the 1910s, because the applied research required to generate the necessary engineering data had not yet been done. Divall's views on unit operations are similar to Donnelly's: that it was 'sufficient to distinguish chemical engineering both from mechanical engineering and from chemistry' and also that, in teaching, it was in tune with the prevailing opinion of British academics and industrialists that students should be taught 'the general principles that informed practice'.[70] He rightly emphasizes the importance of the design of plant in the development of chemical engineering, but, like Donnelly, he ignores the possibility that the discipline could have emerged without unit operations (the origin of which he traces back to Davis).[71] The assumption made by Donnelly, Divall and other writers that chemical engineering could not have existed without unit operations, necessarily requires them to show that unit operations was present at the birth of chemical engineering. In fact, it seems to me that there is no reason in principle why academic chemical engineering could not have developed from its beginnings in the 1880s to its modern state *without* unit operations, and I offer a suggestion as to how this might have occurred. The event which seems to have signalled the eventual demise of unit operations as a research topic was the publication in 1960 of Bird, Stewart and Lightfoot's *Transport Phenomena*.[72] This book was written, according to the authors' preface: 'Because of the current demand in engineering education to put more emphasis on understanding basic physical principles than on the blind use of empiricism'. This suggests an interesting shift of engineering education policy rather than any failure of empiricism, and indeed the 'blind use of empiricism' was by no means entirely abandoned by Bird, Stewart and Lightfoot, who include in their book a number of approximate and graphical solutions to problems. But, although the text of *Transport Phenomena* is largely a complex mathematical treatment of mass, energy and momentum transfer in a variety of physical systems commonly encountered by chemical engineers,

69 Donnelly, 'Chemical engineering', op. cit. (2), 584.

70 Expressed in his 1994 paper 'Education for design' (Divall, op. cit. (2), 267–8).

71 Divall, 'Education for design', op. cit. (2), 270.

72 R. B. Bird, W. E. Stewart and E. N. Lightfoot, *Transport Phenomena*, Madison, 1960.

there is no theoretical reason why such a mathematical approach to these problems could not have been written in 1920.

Nevertheless, unit operations was a significant source of engineering knowledge for over half a century, but, as I have shown, it was only a *part* of chemical engineering, which might even have emerged without it. For most other authors, unit operations was the most significant factor in differentiating chemical engineering from its neighbouring disciplines. How then, if unit operations had not existed (as I have suggested was at least possible) would chemical engineering have been distinguished from chemistry and mechanical engineering? Well, the term 'chemical engineering' had slowly become current in England after 1850, describing the use of mechanical equipment and devices in the chemical industry. As a job title, 'chemical engineer' came somewhat later, but, by 1882, one member in twenty of the Society of Chemical Industry had adopted it.[73] Some thirty years later, it was obvious to the practitioners of the early twentieth century (Arthur Little or John Hinchley, for example) that chemical engineering was a new and exciting discipline: it was unique in dealing with the large-scale production of materials under controlled conditions, where physical and chemical changes might occur simultaneously. Neither chemists nor mechanical engineers were routinely trained to tackle the economic production of chemicals on an industrial scale. Therefore, with or without unit operations, there are many important aspects of large-scale chemical production which would not have been covered in chemistry or mechanical engineering curricula, leaving plenty of scope for the formation of a new discipline called chemical engineering.

PROFESSIONAL INSTITUTIONS OF CHEMICAL ENGINEERS

We have seen that successful chemical engineering courses first became established in both London and Boston in departments of chemistry.[74] Similarly, both the Institution of Chemical Engineers (IChemE) and the AIChE grew out of chemical, not engineering, societies. Sixteen years after the first undergraduate course in chemical engineering was inaugurated at Boston Tech, Richard K. Meade founded the *Chemical Engineer*. The following year, and again two years later in 1907, Meade argued in an editorial that, in view of the increasing number of American colleges which were now producing graduates in the new discipline, the time was right to consider the formation of a professional society for chemical engineers. Meade followed up his editorial initiative by organizing a meeting of interested practitioners, and the views of 600 North American chemists were canvassed. A large majority was in favour of a new society with high entrance qualifications. Unsurprisingly, the president of the ACS, M. T. Bogert, was opposed to the idea, and announced instead a new publication, the *Journal of Industrial and Engineering Chemistry*,

73 Donnelly, 'Chemical engineering', op. cit. (2), 557.

74 Indeed, a large majority of all the university courses in chemical engineering founded before 1940 arose in departments of chemistry. See Westwater, op. cit. (14), 145, 147 and 150. Westwater analysed all of the chemical engineering departments in the United States: fifty-six originated in departments of chemistry, thirteen in assorted engineering departments and seventeen were founded as free-standing departments. In the case of the pioneering departments at Boston Tech and Imperial College, it was thirty-three years and twenty-six years respectively before chemical engineering became separated from chemistry and associated with the faculty of engineering.

and the proposal to form a Division of Industrial Chemistry and Chemical Engineering within the ACS, as a way to satisfy the evident demand for a society which would serve the interests of chemical engineers. Despite the vehement opposition of the ACS, the foundation of the AIChE formally took place in June 1908. Within months, the ACS had reacted by creating not only the promised Division of Industrial Chemistry and Chemical Engineering, but also the Division of Fertilizer Chemistry, and a number of other divisions aimed at preventing the defection of further splinter groups.

The leaders of the AIChE were immediately aware of the potential for conflict with the much older and financially more secure ACS, and wisely adopted policies which avoided antagonizing the ACS. In the first two decades after the AIChE was formed, the most important of these policies was the qualification for membership. Eligibility was restricted to those over 30 years of age who were proficient in both chemistry and engineering, actively involved in the application of chemistry in industry, with at least five years' experience (ten years for non-graduates) and five years' service in a senior management position. These élitist membership qualifications precluded most academics from membership, and indeed most chemists. However, a number of senior figures (industrialists, consultants and academics) who had promoted the creation of the AIChE were long-standing members of the ACS, and therefore had an interest in the establishment of a *modus vivendi* for the two organizations. Arthur Little and William Walker had both been instrumental in the formation of the AIChE, but neither joined it at once. Little became chairman of the ACS's rival Division of Industrial Chemistry and Chemical Engineering, and both he and Walker joined the editorial board of the ACS's new *Journal of Industrial and Engineering Chemistry*. In 1912 and 1913, Little was president of the ACS, and in 1919 he was president of the AIChE.[75]

In the years after the foundation of the AIChE, the growth of the American chemical industry was very rapid, but this expansion inevitably slowed during the depression of the 1930s.[76] Membership of the AIChE had increased from 40 in 1908 to 805 in 1929. As early as 1919, Little had advocated the relaxation of the strict entry qualifications in order to admit eminent academics and others, but members voted against, preferring to maintain their reputation as an élite group. However, in 1930, the American Society of Mechanical Engineers proposed to form a Process Industry Division. Members of the AIChE became concerned that if their restrictive rules of enrolment continued, young engineers would be attracted to this new Division, and that in time the AIChE would lose its mandate to speak for the profession. Those in favour of broadening the membership pointed out that the discipline was now well established, so that proficiency in chemical engineering (as opposed to chemistry *and* engineering) should be the main criterion for entry. After considerable debate, agreement to change the regulations was accepted by a narrow margin in 1931. Subsequently, despite the depression, membership of the AIChE more than doubled between 1929 and 1938. Having begun its life as an offshoot of the chemistry

75 Reynolds, op. cit. (60), 6–9.

76 See L. F. Haber, *The Chemical Industry During the 19th Century*, London, 1958, 143, and op. cit. (11), 320, in which the value of the production of the United States chemical industry is said to have grown as follows: 1900, \$63m; 1913, \$833m; 1927, \$2313m. Output in the record year of 1929 was not surpassed until 1937. See Reynolds, op. cit. (60), 27.

profession, the final incorporation of the AIChE into the engineering establishment occurred in 1958, when the AIChE bought itself into the United Engineering Trustees, and established its headquarters in the Engineering Societies Building in New York, alongside the civil, mechanical, electrical and mining engineers.[77]

Within twenty years of the inauguration of Boston Tech's pioneering undergraduate course, there were over a dozen chemical engineering degrees available in the United States, but the curricula varied widely.[78] The founders of the AIChE set up an Education Committee at their first regular meeting in December 1908, but it appears not to have achieved a great deal until 1920. It was re-formed in December 1919 under the chairmanship of Arthur Little, with a brief to consider what steps the AIChE could take towards increasing the competence of chemical engineering graduates. Contact was made with 128 institutions believed to offer courses relevant to chemical engineering; by the end of 1920, information on 77 of these was being analysed. The Committee's report was presented in 1922: it was based on the premise that chemical engineering was a 'science of itself, the basis of which is...unit operations'.[79] Having recommended unit operations as the core of the chemical engineering curriculum to Boston Tech in 1915, Little now applied the same thinking to the profession as a whole. His report was welcomed, and later in 1922 a new Committee was charged with the task of publishing, within three years, the names of those academic institutions which offered 'satisfactory' chemical engineering courses. In June 1925, a list of fourteen institutions was announced, with a recommendation to the AIChE to set up a review procedure by which the list could be increased. The proposal by the Committee that chemical engineering departments should be administered within colleges of engineering (rather than of chemistry) met with some opposition, but was eventually accepted. Indeed, the whole principle of accreditation of courses by the AIChE, initially opposed by a sizable minority of the membership, was confirmed in 1927, and by 1931 there were eighteen accredited institutions. In this way, the AIChE succeeded in assigning a key role in chemical engineering to unit operations, locating the discipline firmly within faculties of engineering, and differentiating the profession from its neighbouring disciplines. In order to survive as an independent profession, chemical engineers had had to define and establish their discipline, and by the manner in which this was achieved, they put themselves in a position of control over academic curricula which the older engineering disciplines did not achieve for another ten years.[80]

The year after the AIChE was founded in the United States, John Hinchley began teaching his chemical engineering course at Battersea Polytechnic. Six years after that, in 1915, the *Chemical Trade Journal* (founded by George Davis and his brother) advocated the formation of an Institution of Chemical Engineers, but although the proposal met with some positive response from works chemists, it was powerfully opposed by the Society of Chemical Industry. However, in 1918, Hinchley, now assistant professor of chemical engineering at Imperial College, and others, suggested the creation of a Chemical Engineering Group *within* the Society, and this time a committee was formed to prepare

77 Reynolds, op. cit. (60), 47.
78 Reynolds, op. cit. (60), 10.
79 Reynolds, op. cit. (60), 13.
80 Reynolds, op. cit. (60), 14–15.

a constitution. Hinchley was chairman of the steering committee, which successfully guided the new Chemical Engineering Group through its inauguration in 1919. He told the Inaugural Meeting of the need to establish the existence of chemical engineering as a distinct profession. This was to be done (said Hinchley, speaking in the same year that Little began work at the AIChE on accreditation) through appropriate training. An article, possibly written by Hinchley, which appeared in *Chemical Age* in 1920, criticized the suggestion that chemical engineering was a branch of mechanical engineering, quoting curricular development in the United States, in which the civil and mechanical engineering content of courses was being reduced. These developments, said the article, were mirrored in the department of chemical technology at Imperial College, and this confirmed that chemical engineering was indeed a 'definite science'.[81] In 1921, Hinchley used the occasion of the annual general meeting of the Chemical Engineering Group of the Society of Chemical Industry to propose the formation of an independent Institution of Chemical Engineers. One hundred members expressed interest, and the following year, the IChemE, with Hinchley as secretary, was incorporated under the Companies Acts, despite objections from the Institute of Chemistry and the Institution of Civil Engineers.[82]

Early this century, before the formation of the IChemE, the professional institutions of the civil, mechanical and electrical engineers in Britain had set their own qualifying examinations. Students at technical colleges often sat these examinations, while the holders of approved university degrees were granted exemption. Like its American counterpart, the IChemE acted as a forum in which industrialists could negotiate with academics to achieve a mutually acceptable undergraduate curriculum. Divall points out that 'the list of subjects judged to be distinctive of chemical engineering' was very similar to that recommended by Arthur Little to Boston Tech in 1915.[83] Specifically, unit operations and the economic evaluation of plant played important roles in courses recommended by the professional institutions on both sides of the Atlantic to universities seeking accreditation. Divall acknowledges that by 1922 the chemical engineering course at MIT (as Boston Tech had become known) was being held up as a model in London. But he believes that 'on the balance of probabilities' Hinchley's earlier course of 1910 was not inspired from Boston, but drew on George Davis's ideas.[84] I am sceptical that Davis's 1901 textbook amounted to much more than a sensible ordering of pieces of plant for descriptive purposes, and I am therefore more inclined to believe that Hinchley was indeed aware of and informed by William Walker's courses at Boston Tech and Harvard, which had started in 1905. In his biography, Hinchley's wife does not mention any specific liaisons with American academics, but she does report that one of the first papers published in the *Transactions of the Institution of Chemical Engineers* was submitted by workers at MIT, suggesting an early relationship between that institution and Hinchley or his associates.[85]

Given the financial stringency imposed on most British universities between the Wars, Divall deduces that the IChemE had to spend proportionately more effort than the AIChE

81 Donnelly, 'Chemical engineering', op. cit. (2), 581–3.
82 Donnelly, 'Chemical engineering', op. cit. (2), 583.
83 Divall, 'Education for design', op. cit. (2), 267.
84 Divall, 'Education for design', op. cit. (2), 269.
85 Edith M. Hinchley, *John William Hinchley, Chemical Engineer*, London, 1935, 69.

in convincing universities to invest in chemical engineering facilities.[86] However, although Britain lacked major philanthropic foundations such as the Rockefeller, which assisted MIT and other American institutions, colleges in London were indeed able to expand their chemical engineering departments. The department of chemical technology at Imperial College, where Hinchley taught his course in chemical engineering, for example, managed to increase its research programme steadily throughout the 1930s. When (in 1938) Imperial College offered an undergraduate programme for the first time since Armstrong's course was wound up in 1911, they were able to advertise the existence of no fewer than twenty-six research topics (there had been none in 1920) in which postgraduates could work for the M.Sc. or Ph.D.[87]

Despite differences of education system and industrial organization in Britain and the United States before 1925, therefore, there existed professional societies for chemical engineers, which embraced unit operations as an important element of chemical engineering, and which actively sought to influence the chemical engineering curricula offered by university departments.

SEPARATE TRANSATLANTIC DEVELOPMENT OF CHEMICAL ENGINEERING: FACT OR FICTION?

Writing in 1977, Hougen stated that in Germany the chemical engineer was regarded as an 'unnecessary hybrid...not accepted...until recently'.[88] In similar vein, in 1979, Schoenemann quoted the following headline which appeared in *Chemical Engineering News* in 1956: 'Chemical Engineering New to the United Kingdom, Unknown in Germany'. This encapsulates the view widely held by chemical engineers and historians that chemical engineering was an American invention which did not reach Britain until the Second World War, nor Germany until the 1960s.[89] More recently, Scriven, after discussing the establishment of series of books on chemical engineering by the two American publishing houses James H. McGraw and John Wiley & Sons, in the 1920s and 1930s, stated that: 'Nothing like these series of books appeared in Europe, where there were neither comparable university courses, nor numbers of students, nor professional society, nor committed industrial executives'.[90] There is no justification for this sweeping statement. There are several reasons why American-style series of textbooks may not have been published in Britain or Germany, but, even though they were not, the American books themselves were available, and were used in Europe. Scriven (like Schoenemann) goes on to describe some important German textbooks of the 1930s, so that, even without American books, work which covered state-of-the-art chemical engineering was being published in Europe. Similarly, the university courses available in Britain, while different in detail, and not as numerous as in the United States, nevertheless covered the same topics at more or less the same time as the leading American institutions. This point is illustrated

86 Divall, 'Education for design', op. cit. (2), 265.
87 *Calendar*, op. cit. (32), 1919/20, 156, and 1938/39, 186–7.
88 Hougen, op. cit. (1), 93.
89 Schoenemann, op. cit. (13), 250.
90 Scriven, op. cit. (1), 27.

Table 1. *Earliest research in selected topics at Wisconsin University and Imperial College*

Subject	Wisconsin (First thesis)[a]	Imperial (First mentioned in post-graduate course or research topics)[b]
Unit operations	1924	1919
Process control	1934[c] (1954)	1952
Reaction rates & catalysis	1941	1928
Thermodynamics	1943	1927
Spray technology	1948	1950
Diffusion	1955	1960
Process engineering	1966	1964

a The theses tabulated by Hougen were seniors', masters' and doctoral. I have taken the earliest in each case, regardless of degree. Theses by seniors (undergraduates) were phased out around 1915.

b The references can be found in the Imperial College Archive, *Calendar*, op. cit. (32): unit operations is first mentioned in the *Calendar* for 1919/20, 155; process control, 1952/53, 113; reaction rates and catalysis, 1928/29, 184; thermodynamics, 1927/28, 190; spray technology, 1950/51, 99; diffusion, 1960/61, 171–2; process engineering, 1964/65, 210.

c This was a master's thesis. Theses in process control, whether masters' or doctoral, do not appear regularly until 1954. 'Process measurements and control' was added to the Wisconsin undergraduate programme in 1944.

by the comparison in Table 1 of the development of chemical engineering at Wisconsin from 1919 to 1966 with that at Imperial College.[91] The IChemE was formed in England in 1922, so that to say (as Scriven does) that there was 'no professional society' in Europe at the time is simply not true. Finally, Scriven's comment that there were no 'committed industrial executives' who were chemical engineers is similarly unsupportable. Ignoring graduates from Armstrong's department at the Central Institution from 1888, there was certainly a steady stream of chemistry (and other) graduates trained in chemical engineering at Imperial College from 1912, plus alumni from Glasgow, University College and King's College, London, and Manchester from 1927 onwards. An increasing number of these would most certainly have been committed industrial executives from 1920.

Guédon states that chemical engineering emerged as an academic discipline in Britain only after the First World War, following the example of the United States.[92] According

91 See Hougen, op. cit. (1), 101; and *Calendar*, op. cit. (32). For detailed references see Table 1, note *b*.

92 Guédon, op. cit. (12), 47 and 51–3. Guédon takes a typically 'declinist' view of the British chemical industry, explaining that although Britain led the world in heavy inorganic chemical production in the 1850s, its industry was dominated by a conservative management who saw no need for scientific research. Later, Britain was unable to benefit from newer technologies which emerged from the Continent after 1870, owing to a lack of trained scientists in general, and of chemists in particular. The British at last realized their error (says Guédon) and began training more chemists. However, this did not solve the problems of the British chemical industry, because in the early years of the twentieth century, too many of these valuable graduates went into teaching. This interpretation was common at the time when Guédon was writing (1980), but it was based on an estimate of the number of chemists in Britain before 1914 which has since been comprehensively criticized in D. E. H. Edgerton, 'Science and technology in British business history', *Business History* (1987), **29**, 103.

Table 2. *Membership of chemical societies*

	Year	Number of members	National population (1910, millions)
Academic chemists			
American Chemical Society	1912	5600	92
Chemical Society, London	1911	3100	41
Deutsche Chemische Gesellschaft	1912	3300	58
Industrial chemists			
Society of Chemical Industry (British)			
(a) British members	1905	4000	
(b) US members	1906	1500 (half of whom are also members of ACS)	
Academic and industrial chemists	1912	3000	
Institute of Chemistry (Britain)			
Verein Deutscher Chemiker	1909	4000	

to Guédon, the British were slow to train chemists for industry. However, Table 2 suggests that there were large numbers of chemists in all three leading chemical-producing nations.[93] (I do not present Table 2 as a comprehensive or wholly accurate record of the numbers of chemists in Britain, Germany and the United States, but merely to show that these numbers were substantial.) In a more studied approach to the employment of chemists in British industry at the turn of the century, Donnelly points out that 'chemistry [was] quantitatively and institutionally the most developed of the sciences at that time'.[94] Contradicting Guédon, Donnelly finds that many chemists *did* go into industry, and moreover that it was the better qualified men who did so, attracted by the salaries on offer, which were higher than those available in teaching.[95] Valued initially for their skills in chemical analysis, the more able chemists found their way into process management, or into early industrial research and development.[96] This picture is reinforced by Haber's comment that 'at the seventh [World's] Congress [of Chemists] in London (1909) there were over 3000 registrations'.[97]

93 Membership of chemical societies from Haber, op. cit. (11), 35–7. These figures are approximate. In all countries there were chemists who were members of more than one society. Population figures are from: US Department of Commerce, Bureau of the Census, *Historical Statistics of the United States from Colonial Times to 1957*, Washington, 1960; B. R. Mitchell, *Abstract of British Historical Statistics*, Cambridge, 1962; K. J. Bade, *Population, Labour and Migration in 19th. and 20th. Century Germany*, Leamington Spa, 1987. Where necessary, in both the membership and population statistics, I have made linear interpolations to obtain figures for years for which they are not given in the sources.

94 J. Donnelly, 'Industrial recruitment of chemistry students from English universities: a revaluation of its early importance', *BJHS* (1991), **24**, 6.

95 Donnelly, op. cit. (94), 17–18.

96 Donnelly, op. cit. (94), 20.

97 Haber, op. cit. (11), 34.

In his recent paper, Divall seems to accept Guédon's description of chemical engineering in Britain as running a poor second, some years behind America.[98] He concludes that the IChemE was initially ineffective in breaking down the traditional division of labour within the chemical industry (in which plant design, operation and management were supposedly divided between chemists and mechanical engineers). Consequently, says Divall, employment of chemical engineers, and therefore the membership of the IChemE, grew only slowly.[99] 'As late as 1940', according to Divall, IChemE had 'only 761 members', a figure which the AIChE exceeded ten years earlier. But Divall's comparison of the IChemE's membership with that of the AIChE is open to question. If we take Divall's year (1940) and relate the numbers of members of the British and American institutions to the sizes of the populations of Britain and the United States, the number of IChemE members per head is very similar to that of the AIChE.[100]

Why, then, have scholars taken the view that chemical engineering evolved separately and differently in Britain and the United States? First, national expectations seem to be satisfied by the simple scenario that the British invented chemical engineering and the Americans developed it. This scheme fits the widely held (but now discredited) view that Britain has suffered an economic decline since the 1870s, after failing to capitalize on many inventions owing to a lack of investment in scientific and technological education and research.[101] Secondly, the exact definitions of 'chemical engineering' and 'chemical engineer' were problematic in 1880, and not entirely resolved until the 1960s. This was illustrated earlier by reference to the evolution of the course at Imperial College from 1913 to 1965. The fluid nature of early chemical engineering left considerable room for misunderstanding about how the discipline was developing outside one's home country. Nevertheless, we see from Table 1 that chemical engineering curricular developments at Wisconsin were similar to those at Imperial College from the early 1920s, and we know that academics at Imperial were well aware of developments in chemical engineering at MIT, so that teaching and research were likely to be comparable at all three institutions.

But if, as I suggest, chemical engineering has progressed internationally along almost identical lines for most of its history, why should this be so? One reason was the international nature of the trade in chemicals. Following the discovery of oil in Sumatra in 1890, for example, the Royal Dutch Company was formed, and by 1903 it was operating a refinery in Rotterdam. From 1886, Scottish interests developed the Burmese oilfields which by 1914 were producing 2 per cent of the world's total oil output.[102] In a different sector, as a result of one of the many international commercial alliances formed in the

98 Divall, 'Education for design', op. cit. (2), 264–7.

99 Divall, 'Education for design', op. cit. (2), 264–5.

100 Given that the population of Britain was 47 million, and that of the United States was 132 million in 1940, membership of IChemE of 761 would imply a membership of AIChE of about 2140, assuming both countries had the same number of chemical engineers per head. The actual membership of AIChE was 2255: only 5 per cent different from the 2140 calculated on the basis of population difference alone.

101 In his pamphlet *Science, Technology and the British Industrial 'Decline', 1870–1970* (forthcoming), David Edgerton demonstrates convincingly that 'despite constant arguments that scientists and engineers had more influence in other countries, British higher education, the British state, and British industry were, if anything, peculiarly scientific and technological'.

102 R. W. Ferrier, *The History of the British Petroleum Company*, 2 vols., Cambridge, 1982, i, 1–3.

chemical industry before 1914, the General Chemical Company of America and the German company BASF exchanged patents and other agreements, as well as technical know-how.[103] Later, the First World War exposed the strategic vulnerability of individual nations to interruptions of supplies of commodities, especially dyestuffs, nitrates and hydrocarbon fuels. Nations took action to ensure self-sufficiency in future.[104] Another consequence of war was that German technology was made available to the allies after 1918, and again after 1945. For reasons of international trade and national interest, therefore, there was early and comprehensive transfer of technology among nations, a process which was accelerated by the World Wars. But there is a more basic reason why chemical engineers would at least have started working along similar lines in Britain and the United States (as well as Germany) in the first two decades of the twentieth century. Many academic chemists in Britain and the United States at that time, having gained their first degrees at home, travelled to Germany for their Ph.D. studies. The qualified men of all three countries had received identical training.[105]

CONCLUSION

Independent consultants calling themselves chemical engineers emerged in England in the second half of the nineteenth century, and chemical engineering courses first appeared in university-level colleges in Britain and the United States in the 1880s. However, it was not until about 1910 that these courses became firmly established, and it seems that the invention of unit operations (whose earliest proponents were probably William Walker and his associates in Boston and John Hinchley in London) played an important part, not in the founding of chemical engineering but in its establishment as an independent academic discipline. Professional institutions of chemical engineers in both Britain and the United States were influential from the 1920s in shaping university curricula, and this close cooperation between practitioners and academics, particularly characteristic of chemical engineering, further promoted its differentiation from neighbouring disciplines. Unit operations, in common with other aspects of chemical engineering, developed along parallel lines at substantially the same time in Britain and the United States.[106] Although there are variations of detail among the ways in which technology develops in different countries, the international character of the chemical industry, and the effects of the two World Wars on nations' perceptions of their strategic interests, have powerfully assisted the rapid transfer of chemical engineering knowledge across the Atlantic in both directions.

103 Trescott, op. cit. (16), 15.

104 Haber, op. cit. (11), 184–217.

105 The importance of German sources to early students of chemical engineering is emphasized by the inclusion of the study of German in Henry Armstrong's course at the Central (op. cit. (34)). Hougen, op. cit. (1), 91, notes that 'A reading knowledge of German was required' of the first chemical engineering students at Wisconsin.

106 In this respect, the situation was similar to that found by Edgerton and Horrocks for industrial R & D, namely, that it 'may be that British firms were more like American firms, or German firms, than historians have allowed'. See D. E. H. Edgerton and S. M. Horrocks, 'British industrial research and development before 1945', *Economic History Review* (1994), **47**, 235.