SCALING UP: THE EVOLUTION OF INTELLECTUAL APPARATUS ASSOCIATED WITH THE MANUFACTURE OF HEAVY CHEMICALS IN BRITAIN, 1900-1939

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Introduction

At the turn of the century, men trained in chemistry but not in any of the engineering disciplines held sway over the technical side of much of the business of chemical manufacturing in Britain. However, the growing economic importance of bulk chemicals after around 1880 had been accompanied by the emergence of new specialists in the design and operation of chemical plants. This became particularly significant with the widespread introduction of high pressure equipment from around 1920.[1] The outcome was that by the outbreak of World War II chemists were under some pressure to cede certain of these responsibilities to a new breed of technical worker, the chemical engineer.

All would-be professions have to claim and maintain jurisdiction over a class of occupational practices if they are to prosper, and the evolution of chemical engineering serves to illustrate the importance of intellectual apparatus for this process.[2] Although only loosely defined and poorly organized before World War I, chemical engineers promised a different way of organizing the production of heavy – or bulk – chemicals. In tandem with these new industrial practices, practitioners and educators developed a new way of conceptualizing chemical manufacturing. With the establishment in 1922 of a professional organization, the Institution of Chemical Engineers, great effort was put into defining and promoting chemical engineering as a subject that came to be taught

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[1] For the technical problems, organization and personnel involved in such work see, for example, Victor E. Parke, *Billingham - The First Ten Years* (Billingham: Imperial Chemical Industries, 1957).

[2] Andrew Abbott, *The System of the Professions* (Chicago: Univ. Chicago Press, 1986), pp. 52-58.

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quite widely as a separate discipline at the university level. If by 1939 chemical engineers could claim some standing within industry, it was at least in part because of a growing acceptance that the intellectual framework of chemical engineering amounted to more than just a synthesis of earlier technical disciplines.

Most historical studies of chemical engineering focus on the emergence of the profession in the United States, and they tend to assume that the intellectual substance of chemical engineering in Britain was almost entirely the result of American influences.[3] Some scholars have highlighted certain national differences in the cognitive scope of the discipline in European countries other than Britain.[4] Only quite recently have historians started to acknowledge the indigenous roots of British chemical engineering.[5] In this chapter we expand on the work of James F. Donnelly and of one of us (Divall), by looking at how the particular circumstances under which chemical engineering emerged as a profession in Britain shaped the associated intellectual discipline.[6]

Conceptual foundations of the chemical engineering profession

Much of the historiography of chemical engineering as a kind of industrial practice and

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[3] Many of these accounts were written by former practitioners; the two principal collections of such material are, both William F. Furter, ed., *History of Chemical Engineering* (Washington, DC: American Chemical Society, 1980), and *A Century of Chemical Engineering* (New York: Plenum Press, 1982). On the US experience see, for example, Martha M. Trescott, "Unit operations in the chemical industry: an American innovation in modern chemical engineering," in *A Century of Chemical Engineering*, pp. 1-18; F.J. Van Antwerpen, "The origins of chemical engineering," in *History of Chemical Engineering*, pp. 1-14; David F. Noble, *America by Design: Science, Technology and the Rise of Corporate Capitalism* (New York: Alfred A. Knopf, 1977), pp. 26-27, 38, 79, 192-195; John W. Servos, "The industrial relations of science: chemical engineering at MIT, 1900-1939," *Isis*, **71** (1980), 531-549; T.S. Reynolds, *75 Years of Progress. A History of the American Institute of Chemical Engineers, 1908-1983* (New York: American Institute of Chemical Engineers, 1983), *passim*; Reynolds, "Defining professional boundaries: chemical engineering in the early 20th century," *Technology and Culture*, **27** (1986), 694-716.

[4] E.g. Klaus Buchholz, "Verfahrenstechnik (Chemical Engineering) - its development, present state and structures," *Social Studies of Science*, **9** (1979), 33-62 and, less convincingly, Karl Schoenemann, "The separate development of chemical engineering in Germany," in *History of Chemical Engineering*, op. cit. (3), pp. 249-272.

[5] J.F. Donnelly, "Chemical engineering in England, 1880-1922," *Annals of Science*, **45** (1988), 555-590; Colin Divall, "Education for design and production: professional organization, employers and the study of chemical engineering in British universities, 1922-76," *Technology and Culture*, **35** (1994), 258-288; Divall, "Professional organization, employers and the education of engineers for management: a comparison of mechanical, electrical and chemical engineers in Britain, 1897-1977," *Minerva*, **32** (1994), 241-266; Clive Cohen, "The early history of chemical engineering: a reassessment," *British Journal for the History of Science*, **29** (1996), 171-194.

[6] Divall, op. cit. (5), and "A measure of agreement: employers and engineering studies in the universities of England and Wales, 1897-1939," *Social Studies of Science*, **20** (1990), 65-112. Donnelly, op. cit. (5), and "Representations of applied science: academics and chemical industry in late nineteenth-century England," *Social Studies of Science*, **16** (1986), 195-234.

a profession has been concerned with its early academic connections. Chemical engineering courses were important because they gave a sense of identity to the would-be profession and made explicit its cognitive scope. Moreover, by providing practitioners with a unique intellectual foundation for the changing techniques of chemical manufacturing and the design of chemical plant, chemical engineers were given the means to exclude competing occupations from these and certain other related kinds of industrial work. But if we are to understand the evolution of the intellectual apparatus of chemical engineering in Britain, we need to be clear about the peculiarities of other countries, and particularly of the United States.

Both Britain and the United States, in contrast to many of the countries of continental Europe, were characterized before World War II by political systems that laid great emphasis on the voluntary, professional regulation of those scientific or technical occupations that commanded social and economic prestige. Similarly, the universities were not subject to any significant measure of control by the state. Thus in both countries intellectual developments relating to the chemical industries were largely a matter of tacit negotiation between academics and certain groups of business officials, consultants and other would-be professionals. But the British chemical industry was by no means identical to the American industry in terms of the markets it served or the typical structure of firms, and advocacy of educational programmes of chemical engineering in the two countries took place under rather different circumstances.

Generally speaking, British chemists and engineers were more firmly entrenched in the industrial division of labour, and enjoyed older and more effective forms of professional organization than did their counterparts in the United States. Chemistry, in particular, was well established as a university discipline. It was therefore more difficult for chemical engineers in Britain to press their claim to professional status, and to establish a novel intellectual underpinning for their expertise. But while the scale of their achievement was perhaps not as great as that in the United States, British chemical engineers nevetherless proved remarkably inventive when it came to defining the intellectual content of their discipline.

Scholars agree that from the 1880s certain groups of technical experts dissatisfied with their standing in the industrial hierarchy made repeated attempts in Britain and the United States to wrest control of certain industrial practices from chemists; in the intellectual realm, this struggle was paralleled by disputes between advocates of, on the one hand, chemistry and, on the other, "chemical engineering." This process was first analyzed by historians working on the United States. Terry Reynolds has shown that by the first decade of the 20th century, groups of senior chemists employed in chemical manufacturing were seeking to distinguish themselves from analytical chemists, who had a low status, by claiming as their own the task of scaling up chemical processes from the laboratory to the industrial level. They were joined by some consultants to the chemical manufacturers, and a number of businessmen.[7] These nascent chemical engineers were opposed by the existing professional society for chemists, the American Chemical Society, the leaders of which argued that the development of new manufacturing processes could be understood within the conceptual framework of industrial chemistry. Mindful of the need to establish its claim to a distinctive specialism, the American Institute of Chemical Engineers (AIChE), founded in 1908, chose to restrict full membership to persons over 30 years of age who possessed several years of practical experience in both chemistry and another branch of engineering. Would-be members also had to be actively involved with the application of chemical principles to manufacturing.[8] Thus early members of the AIChE used their knowledge of theoretical chemistry as a way of distinguishing themselves both from self-trained factory hands and from mechanical engineers who had become involved with chemical plant design.

These measures had some limited success, but, according to Reynolds, the key to legitimating American chemical engineering as a profession was the evolution of a new cognitive base – the unit operation. This conceptual framework was not formally employed in the struggle for professional status until 1922, when the AIChE's Education Committee chaired by Arthur D. Little, head of one of the largest American consulting engineering firms, recommended that it be employed to define the scientific core of academic educational programmes. However the unit operations had already been evolving over a period of twenty years or more in several American universities, chief among which was MIT.[9] Hence Reynolds sees the American profession as being shaped by at least three factors: first, the desire of certain groups of technical workers to differentiate themselves from the more heterogeneous and less prestigious category of 'chemists;' secondly, their appropriation of a cognitive realm (first physical chemistry, and then unit operations) as a way of underpinning claims to technical expertise; and thirdly, a gain in legitimacy in academic, engineering and industrial circles following the successful application of this intellectual apparatus to the design and operation of large chemical plants.

Tracing the origins of concepts is difficult when the inchoate professions that are trying to appropriate them are in a state of flux, and, reflecting this, the intellectual features of chemical engineering up to 1939 have been described in various and inconsistent ways. Olaf Hougen and Franklin J. Van Antwerpen, for example, identify the unit operations

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[7] Reynolds, "Defining professional boundaries," op. cit. (3), pp. 697-708.

[8] Ibid., pp. 697, 706.

[9] By 1905 the concept of unit operations implicitly informed the curriculum of a new chemical engineering course at what was to become MIT. From 1900, William K. Walker, the course instructor, had a close association with the Arthur D. Little engineering consultancy. John Servos has discussed the currency of the notion of unit operations in the US in this early period, showing that Little was linked closely with such concepts in the curricula of American institutions before 1915.

as being crucial from 1916 to 1925, although they also note the increasing importance of material and energy balances to 1935, and of applied thermodynamics and process control from then until the end of World War II, and beyond.[10] However, Gianni Astarita's work on Italy distinguishes unit operations as the sole organizing concept.[11] Clive Cohen largely concurs with this simple genealogy for the United States and Britain, while moving the influence of unit operations back to about 1910, and suggesting that the profession in both countries could have developed on the basis of other – but largely unspecified – intellectual foundations.[12]

All sources agree, however, that the unit operations were first described as such in 1915 by Arthur D. Little. He defined them as discrete physical processes employed in chemical manufacturing, such as distillation, roasting, filtering and condensation. Each described a particular way in which material could be transformed physically, as, for example, by the reduction in size of solid matter, or by the mixing or separation of solids, liquids or gases. These basic processes would be performed in sequence to obtain a final product; while the number and order might vary from one product to another, any manufacturing process could be understood in terms of the same set of building blocks. The steps could either be carried out on batches of material, or performed as a continuous series of processes in which the material is transformed at different locations in a plant.

Accounts of the origins of the unit operations before 1915, however, diverge considerably. Martha Trescott identifies them as almost exclusively an American innovation. While acknowledging that a British consultant, George E. Davis (discussed at greater length shortly) may have described unit operations in his 1901 *Handbook of Chemical Engineering*, she claims that the concept was popularized and integrated with physical chemistry exclusively by American practitioners. Trescott suggests that three national characteristics explain this American 'lead:' first, the American predilection for rational mechanical design, leading to the careful design of equipment intended for specific uses; secondly, the influence of Frederick W. Taylor's system of "scientific management" in American engineering, which stressed the technically and financially efficient division of manufacturing tasks into unitary operations arranged sequentially; and finally, an American willingness to innovate, to scale up industrial processes, and to engage in the production of goods for mass markets.[13]

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[10] Van Antwerpen, op. cit. (3); Olaf A. Hougen, "Seven decades of chemical engineering," *Chemical Engineering Progress*, **73** (1977), 89-104.

[11] G. Astarita, "L Evoluzione dei fondamenti teorici dell ingegneria chimica," *Chimica e Industria (Quaderni dell Ingegnere Chimico Italiano)* (supplement), **8** (1972), 112-114.

[12] Cohen, op. cit. (5), pp. 175-186.

[13] Trescott, op. cit. (3).

Chemical engineering in the United States was certainly associated with the manufacture of chemicals on a large scale. But beyond this, not one of Trescott's observations is particularly convincing. In the first place, the distinctive American system of manufacturing, involving long runs of relatively small items of machinery and consumer goods of a mechanical or electrical nature, was of limited relevance to the design of large chemical manufacturing plants or the bulk production of chemicals, many of which were intermediates destined for further processing.[14] Moreover, as Donnelly argues, and as was often the case from around 1860 (for example William Perkin's mauve process, introduced in 1858, and his, and BASF's, alizarin process of 1869-70) chemical manufacturing on a considerable scale arose from the scaling up of laboratory procedures long before unit operations were conceived, and efforts to rationalize chemical production – particularly by the introduction of labour-saving processes – pre-dated Taylor's activities.[15]

The close connection between unit operations and mass production is, however, remarked upon by other advocates of the pioneering role of the United States. Klaus Buchholz postulates that the practical problems of exploiting the country's vast oil fields played a substantial part in the American genesis of chemical engineering. He puts forward a particular direction of evolution: from market forces and existing chemical technologies, to intellectual concepts and an emergent profession. Attributing the occupation's growth to the "need for mass-production prompted by the expanding market" in petrochemicals from the turn of the century, Buchholz asserts that this pressure promoted the adoption of economical production methods and encouraged the rational design of industrial plants.[16]

More importantly, he claims that the particular technical requirements of petrochemical processing – namely physical operations such as distillation – explain the readiness of US manufacturers to accept the conceptual framework of the unit operations.[17] By contrast to the American case, a unique occupation combining mechanical and chemical expertise failed to coalesce in Germany; the main reasons were that the petrochemical industry there was negligible, and much more complex chemical syntheses dominated the dyestuffs and pharmaceuticals industries. The occupational specialization involved

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[14] David A. Hounshell, *From the American System to Mass Production, 1800-1932: the Development of Manufacturing Technology in the United States* (Baltimore: Johns Hopkins University Press, 1984), *passim*; John K. Brown, *The Baldwin Locomotive Works, 1831-1915. A Study in American Industrial Practice* (Baltimore: Johns Hopkins University Press, 1995). Brown finds no unique features in the American context of the capital goods sector.

[15] Taylor's first paper on scientific management appeared in 1895; he died in 1915, but Taylorist analysis and management were widely applied in American industry through the inter-war period.

[16] Buchholz, op. cit. (4), 42.

[17] Ibid., p. 37.

in *Verfahrenstechnik* was organized around specific industrial products and their manufacturing processes, and chemical plants were designed and maintained by a combination of chemists and mechanical engineers with a strict division of labour.[18] In a similar vein, Jean-Claude Guédon argues that US manufacturers, particularly in the petrochemical industry, were much more welcoming towards unit operations than the British, and that the American system of higher education was more receptive to the new conceptual framework.[19]

Yet Buchholz says that neither the American experience nor the concept of unit operations were essential for the solution of the problems of expanding industrial production in petrochemicals.[20] Neither, it should be pointed out, was the establishment in the United States of the profession of chemical engineering and its associated intellectual apparatus the inevitable outcome of the growth of the manufacture of bulk petrochemicals. This particular market certainly provided fertile ground for the emerging profession in the United States. However, gaining a measure of acceptance for a novel conceptual framework also required agreement between academics, chemists and engineers working in the chemical industries, and their business leaders, that this was to their mutual advantage. We must therefore examine just how successfully such an alliance was constructed in Britain.

The origins of chemical engineering in Britain, 1900-1914

In their efforts to organize as a profession, British chemical engineers faced a higher degree of organized opposition from other groups of technical workers than their counterparts in the United States. Also, wider developments in the chemical industries that were largely outside their control proved less than favourable. Thus although there were striking similarities between the evolution of key intellectual concepts in the two countries, it is arguable that by 1939 the academic definition of chemical engineering was not as firmly established in Britain as it was in the United States.

In the late 19th and early 20th centuries, the most significant portion of the British chemical industry was, like that in the United States, involved with the bulk manufacture of mainly inorganic products such as bleaching powder, alkali and sulphuric acid. Organic chemicals, particularly coal tar products, and fertilisers began to

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[18] Ibid., pp. 38, 44-51.

[19] Jean-Claude Guédon, "Conceptual and institutional obstacles to the emergence of unit operations in Europe," *History of Chemical Engineering*, op. cit. (3), pp. 45, 56.

[20] Buchholz , op. cit. (3), p. 37. Other historians reverse Buchholz's arrow of causality. Van Antwerpen, for example, concludes that the explosive development of large-scale chemical plants had to await the development of chemical engineering as a distinct engineering discipline [Van Antwerpen, op. cit. (3), 11]. We suggest that the co-evolution of professional organizations, academic concepts and industrial practice is a more realistic evaluation.

assume a growing importance by the turn of the century.[21] Firms manufacturing these products in the English industrial regions of Lancashire, Merseyside and Tyneside, and in Scotland on Clydeside, began to employ growing numbers of specialist workers from the 1860s. But until the last quarter of the 19th century, technical innovation relied more upon empirical developments than on organized scientific research by trained investigators. Production processes were dominated by mechanical plant, and improvements in these, such as a better roasting device for sulphur extraction, were introduced by mechanical engineers assisted, rather than directed, by chemists.[22]

This empirical tradition began to falter in the last decades of the century partly because of the more complicated developmental work and manufacturing techniques associated with the rise of synthetic dyes, itself a response to rising international competition, especially from Germany.[23] The British alkali industry, still reliant on the LeBlanc soda process, saw its exports captured by overseas manufacturers employing the newer and more efficient Solvay process.[24] Meeting these challenges required a more specialized approach to the design and operation of chemical plants; by the end of the century, a rough and ready division of technical labour was fairly well established.[25]

Chemists and engineers had largely proved capable, however, of claiming jurisdiction of the slowly evolving industrial order. Works chemists usually were responsible for the technical supervision of manufacturing processes and managing the labour force; this gave them a status far superior to the analytical chemists that made up the greater proportion of the skilled workforce. Chemists also helped to scale up manufacturing processes from the laboratory to the industrial level in the few firms, such as those manufacturing organic products, in which the development of new chemicals was

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[21] On the British heavy chemicals industry, see, for example, L.F. Haber, *The Chemical Industry During the Nineteenth Century: A Study of the Economic Aspect of Applied Chemistry in Europe and North America* (Oxford: Clarendon Press, 1958); Haber, *The Chemical Industry (1900-1930): International Growth and Technological Change* (Oxford: Clarendon Press, 1971); M. Boas Hall, "La croissance de l'industrie chimique en Grande-Bretagne au XIXe siècle," *Revue d'Histoire des Sciences et Leurs Applications*, **26** (1973), 49-68. On the alkali industry, see K. Warren, *Chemical Foundations: The Alkali Industry in Britain to 1926* (Oxford, 1980) and Frank Morton, "A short history of chemical engineering in the North-West of England," *A Century of Chemical Engineering*, op. cit. (3), pp. 19-28.

[22] Guédon, op. cit. (19), pp. 45-75.

[23] Ibid., esp. 47-52.

[24] Haber, *The Chemical Industry During The Nineteenth Century*, op. cit. (21), pp. 10-11.

[25] Robert F. Bud and Gerrylynn K. Roberts, *Science Versus Practice: Chemistry in Victorian Britain*, (Manchester: Manchester University Press, 1984), pp. 111-117; J.F. Donnelly, "Consultants, managers, testing slaves: changing roles for chemists in the British alkali industry, 1850-1920," *Technology & Culture*, **35** (1994), 100-128. See also Colin A. Russell, with Noel G. Coley and Gerrylynn K. Roberts, *Chemists by Profession: The Origins and Rise of the Royal Institute of Chemistry* (Milton Keynes: Open University Press, 1977).

comparatively commonplace; they were often assisted in this task by engineers. But within all of these neat designations, actual responsibilities could vary widely, particularly in the myriad small firms that provided much of the country's chemical output.[26] Manufacturing plants were increasingly designed, and sometimes erected, by consultants trained either in engineering or in chemistry, or even elements of both. Small firms, lacking the resources to develop their own expertise, were particularly reliant on consultants.[27]

The strength of the professional organizations for chemists and engineers partly explains why, compared to the United States, there was less of a sense of urgency in Britain of the need to establish an autonomous organization and identity for chemical engineers. The Institute of Chemistry (founded in 1877) and the Institution of Mechanical Engineers (1847) catered for many of the more senior workers in the chemical industries. The term "chemical engineer" was used by a handful of specialists in plant design and the management of chemical works, but their attempts in the 1880s to establish an autonomous organization had foundered in the face of opposition from some industrialists and the Institute of Chemistry. The Society of Chemical Industry (1881), a learned society which lacked the constitutional powers to engage with matters of professional concern regarding education, was the rather unsatisfactory alternative open to those manufacturers, chemists and consultants who were unhappy with the leading societies.[28]

The professional societies enjoyed a large measure of influence with academics. Of all the scientific subjects, chemistry was the best established in the universities, and academic chemists successfully guarded their claim to train men destined for industrial employment. From the 1880s, variants such as "industrial chemistry," "applied chemistry," "chemical technology" and even – at the Central Institution, London – one called "chemical engineering" were developed in anticipation of a demand from manufacturers for graduates with skills relating specifically to industry. Despite the increasing availability of these courses, for the most part firms preferred their workers to acquire such knowledge through practical experience.[29] Engineering was less well established as a university subject, but as a source of trained personnel it was rapidly growing in importance by 1900.[30]

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[26] For an anecdotal but revealing practitioner's account of this period, see Norman Swindin, *Engineering Without Wheels: A Personal History* (London: Weidenfeld & Nicolson, 1962), *passim*.

[27] See, for example, Sydney Gregory, "Hugh Griffiths and consultancy," *Chemical Engineer*, (October, 1986), 3.

[28] Donnelly, op. cit. (5), pp. 581-587; Russell, Coley and Roberts, op. cit. (25), pp. 186ff.

[29] Bud and Roberts, op. cit. (25), pp. 111-117; Donnelly, op. cit. (5), pp. 557-561.

[30] Divall, "A measure of agreement," op. cit. (6), pp. 68-70.

Lacking a distinctive conceptual framework for their work, would-be chemical engineers found it hard to resist the argument that they were no more than a hybrid of chemist and engineer. But this gradually began to change in the early 1900s with the development of new intellectual principles – the unit operations – based initially on the ideas of George E. Davis.

As we have seen, even historians who are keen to propound the American origins of chemical engineering usually cite the work of Davis. A Briton and sometime chemical worker, government Alkali Inspector and consultant, Davis is widely credited with having presented one of the first chemical engineering courses, at the Manchester Technical School in 1887, and publishing the first textbook of chemical engineering.[31] Yet there is some disagreement about the significance of his work, even among historians of British chemical engineering. James Donnelly says that Davis's lecture course "resembled a plant manufacturer's catalogue," and that consultants like him "frequently did not design machinery so much as select and combine that of specialist equipment manufacturers."[32] Following on from this description, and his own examination of manufacturers' catalogues, Clive Cohen has concluded that attributions of the concept of unit operations to Davis are misguided. They confuse, he suggests, a logical ordering by equipment manufacturers of certain standardized kinds of apparatus with an intellectual categorization by an allegedly seminal chemical engineer.[33]

And yet, near-contemporaries cited Davis's text as both novel and useful, and equipment manufacturers found a ready market for standardized items such as boilers and heat exchangers. This suggests that Davis was enunciating a strategy of plant design that was in fairly common – if not widely recognized – use by the consultants of his time. Donnelly, in fact, argues that Davis was constructing a conceptual framework for chemical engineering in the context of certain social and occupational tensions. He sought to define a new intellectual specialism while avoiding two dangers: first, appropriation of the nascent subject by the disciplines of chemistry and engineering (particularly, but not exclusively, of the mechanical kind), and secondly, a possible inadequacy of his lectures and writings owing to manufacturers' demands for confidentiality with regard to the industrial processes to which, as a consultant, Davis had privileged access. Because standard forms of plant equipment were available, and not subject to the constraints of commercial secrecy, Donnelly suggests that machinery "became an important medium for the public conceptualization of industrial chemical activity."[34]

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[31] George E. Davis, *A Handbook of Chemical Engineering* (Manchester: Davis Bros., 1901).

[32] Donnelly, op. cit. (5), pp. 563, 566.

[33] Cohen,. op. cit. (5), pp. 176, 183-184, 189.

[34] Donnelly, op. cit. (5), p. 567.

Donnelly also suggests that the construction of the subject was perceived as a resolution of a problem of higher technical education. If chemical engineering were to exist as a subject of instruction it had to fit in with the prevailing views of British educators, industrialists and leaders of the professional societies concerning the nature of technical education; such courses should emphasize the 'principles' that informed practice rather than seek to develop the detailed competencies required in particular industries.[35] Thus we find a specifically British motive for adoption of the concept of unit operations: pedagogical generality and facility of instruction.

Davis was therefore careful to distinguish chemical engineering from chemistry and its derivatives such as industrial chemistry and chemical technology. Chemical engineering was, he argued, a branch of applied science founded on a specialist blend of commercial and technical knowledge rather than any existing scientific or engineering discipline.[36] He also emphasized the professional consultant's tasks of scaling up technical experiments, dividing chemical manufacturing processes into manageable sub-tasks, and systematizing equipment. Hence the notion of unit operations, in practice if not name, was very likely familiar to those active in the field, and was given a crude but recognizable focus by Davis.

Davis's work was taken up in the academic sphere before World War I by John W. Hinchley, a consultant and specialist in plant design who was later to play a leading role in the founding of the Institution of Chemical Engineers, or IChemE. Hinchley established two courses of instruction in London, one, in 1909, at Battersea Polytechnic for part-time students, the other, a year later, in the chemistry department at the Imperial College of Science and Technology. These appealed largely to students who wished to supplement their training in chemistry. Although the term unit operations was not used at first, there is no doubt that unit operations heavily informed Hinchley's teaching.[37]

Like Davis, Hinchley was acutely sensitive to the need to distinguish chemical engineering from chemistry and engineering. He also insisted that academic courses should inculcate in students the ability to apply theoretical knowledge to the kinds of commercial and technical problems they would face in industry. Both considerations were satisfied by the requirement that students had to undertake the design of "commercial plant." Costing was an important consideration in this exercise, reflecting the recommendations of another consulting engineer from Manchester, Jacob Grossmann, who had urged in a 1906 textbook that the key dimension for the design of

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[35] Divall, "A measure of agreement," op. cit. (6), pp. 78-80.

[36] Donnelly, op. cit (5), p. 564.

[37] Ibid., p. 576; Cohen, op. cit. (5), pp. 178-180.

any chemical plant was its financial viability.[38] Thus Hinchley's students were asked to factor manufacturing processes into discrete operations and optimize their economic return. Employing the results of their laboratory investigations into a particular process, they identified the most economic method of undertaking each unit operation under given conditions. By determining quantitatively the flow of materials through a complete process ("material balance"), and by calculating the requirements for both heating and cooling it ("energy balance"), they arrived by a process of trial and error at that combination of the unit operations which offered the most economic way of producing any given chemical. This method became known as "process design." Hinchley's students, however, had to go much further than this. By drawing on training in civil, mechanical and electrical engineering, they had to complete designs of the manufacturing plant, and even the complete factory ("plant design").

These design projects brought together in a unique fashion the conceptual foci of unit operations, plant-centred design, and economic viability that, on the face of it, had only weak intellectual links. Hinchley's teaching distanced the academic speciality of chemical engineering from those of chemistry and mechanical engineering, and, by demonstrating a coherent approach to academic instruction, helped to make the case for further departments of chemical engineering. By establishing a new language through which consultants and their clients could plan, design and evaluate chemical plant, the new intellectual apparatus also helped to provide would-be chemical engineers with a formalized knowledge with which to underpin their technical expertise, and thus eventually to lay claim to professional status. But success in this lay in the future: there were not many chemical engineers of the kind trained by Hinchley in the British chemical industry before 1914.

Professional organization, plant design and the unit operations

Despite strong opposition from the professional societies for chemists and engineers, a formal organization of chemical engineers, the IChemE, was established in 1922. The institution forged an alliance between a handful of prominent business leaders, educators, consultants and manufacturing chemists of some seniority who were all, for quite different reasons, dissatisfied with existing ways of training chemists and others for industrial posts. It drew up a definition of an intellectual framework of chemical engineering based heavily on Hinchley's work, and was successful in getting this accepted in a handful of universities and some parts of the chemical industry. But progress prior to World War II was less rapid than the institution would have liked, largely because many of the largest chemical firms, and in particular Imperial Chemical Industries (ICI), could see no good reason to abandon the by-then traditional division of labour between chemists and engineers.

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[38] Jacob Grossmann, *The Elements of Chemical Engineering* (London: Charles Griffen, 1906), pp. 123-125; Edith M. Hinchley, *John William Hinchley: Chemical Engineer* (London: Lamley, 1935), pp. 27-30, 40-44.

Consultants dominated the leadership of the IChemE in its early days, and they were particularly influential in defining the intellectual basis of chemical engineering. Their views were shaped by their experiences of designing chemical plants and, in many cases, that of constructing and operating manufacturing facilities for explosives, chemical weapons, dyestuffs and intermediate products that had been sponsored by the state during World War I.[39] This shared background was important for securing agreement within the IChemE over the details of the intellectual framework for chemical engineering, and it proved critical as well for defining the links between the IChemE, industry, government and academe.

The IChemE settled on a set of intellectual principles by 1925; in its fundamentals, this served the profession until well after World War II. The influence of North American ideas cannot be denied. The highly successful enlargement and reconstruction of the explosives industry during 1914-18 had been guided by the design techniques of an American chemical engineer, K.B. Quinan. Close links thereafter between the IChemE and the AIChE ensured a ready awareness in Britain of the American technical literature, especially textbooks. More particularly, the successful programme of chemical engineering at MIT was well enough known in Britain to be presented to the IChemE in 1922 as an ideal to emulate.[40] Not surprisingly, there were striking parallels between the list of subjects judged to be distinctive of chemical engineering that the IChemE published in 1925, and the recommendations of Arthur D. Little's report of 1922 for the AIChE. Both lists placed unit operations at the core of the new academic discipline.

There were, however, marked differences in emphasis. Reflecting the dominance of plant manufacturers and consultants among its leadership, the IChemE made the capacity to design manufacturing plant on a commercial basis central to its definition of the intellectual foundations of chemical engineering. This embodiment of separable chemical stages in discrete equipment was conceptually and practically distinct from the American version of unit operations, and the British also proved quick to adopt new technologies such as control equipment.[41] The continued focus on cost-effective chemical staging of processes also helped to maintain educational programmes for chemical engineers in a more intimate connection with business ideals than did courses for chemists and engineers.[42]

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[39] See, for example, Roy MacLeod, "Chemistry for King and Kaiser: revisiting chemical enterprise and the European war," this volume and *Idem*, "The chemists go to war: the mobilization of civilian chemists and the British war effort, 1914-1918," *Annals of Science*, **50** (1993), 455-481.

[40] Robert Edgeworth Johnstone, "The dark days," *Chemical Engineer* (January 1987), 38-39.

[41] See Stuart Bennett, "The use of measuring and controlling instruments in the chemical industry in Great Britain and the USA during the period 1900-1939," this volume.

[42] IChemE, *The Training of the Chemical Engineer* (London, 1925), 5-6; Russell, Coley and Roberts, op.

There was one other important respect in which British conceptual definitions were more extensive than those current in the United States: not until the mid-1930s was there any significant attempt in the latter country to define a conceptual framework that would function in the domain of *chemistry* as unit operations did for the *physical* analysis of chemical manufacturing. In Britain, by contrast, the 1925 IChemE enumeration listed various "reaction treatments of materials," which were to become more commonly known as unit *processes*, and later still as chemical reaction engineering.[43] The list of treatments included calcining, electrolysis, hydrolysis, oxidation and fermentation. The earlier British emphasis on analyzing the chemistry of manufacturing in a manner analogous to that of unit operations can be attributed partly to the experiences of the earliest educators of chemical engineering. Some, such as E.C. Williams, the first professor of chemical engineering at University College, London and Herbert W. Cremer at King's College in the same city, were trained as chemists and had quite extensive experience of chemical manufacturing. Their educational programmes consequently paid considerably more attention to manufacturing techniques than did, for example, Hinchley's course at Imperial College.[44]

By 1939, six institutions of university rank taught chemical engineering broadly in line with the IChemE's definition; together these bodies had turned out nearly 400 trained men. Indeed, accredited chemical engineers were proportionally more numerous in Britain than in the USA.[45] But it is arguable that the idea of the unit operations and associated concepts was not as convincingly accepted in Britain as in the USA. The links between British educational programmes, professional organization and industrial practice were, on the whole, fairly weak, although there were certain firms and parts of the chemical industry where the connections were strong. Oil companies and coal-gas

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cit. (25), pp. 158-185, 264-283.

[43] Nikolaos A. Peppas and R.S. Harland, "Unit processes against unit operations: the educational fights of the thirties," in N.A. Peppas, ed., *One Hundred Years of Chemical Engineering*, (Dordrecht: Kluwer Academic Press, 1989), pp. 125-142.

[44] The role of manufacturers' interests was also influential in the curriculum. At UCL, the department owed its very existence wholly to the generosity of industrialists, who funded the establishment of a chemical engineering laboratory in 1923. A further appeal four years later to secure the financial future of the department called upon the services of eight leading industrialists from companies such as ICI, Shell, Lever Brothers, Dunlop, and the Gas, Light & Coke Co.

[45] By 1940, there were 761 accredited chemical engineers in Britain (IChemE 'corporate' members) compared with 1349 in the US (AIChE 'active' members). However, the number of student members in the two institutions (for example, 50 in the IChemE versus 1400 in the AIChE in 1932) suggests a significantly higher rate of production in America. This is supported by academic records: by 1940 some 40 American colleges offered degrees in chemical engineering, MIT alone averaging 58 graduates per year between 1920 and 1934. In Britain, the combined output of diploma, certificate and undergraduate degree programmes was some 15-20 per year. For Ph.D.s in chemical engineering, the US rate by 1940 was over fifty per year; the British output was less than one-tenth this figure.

manufacturers proved particularly enthusiastic employers of chemical engineers. But elsewhere, chemical plant was still likely to be designed by mechanical engineers and chemists, and to be operated and managed by chemists alone.

This was undoubtedly partly due to conservative business practices; many plant designers and managers had been trained in Germany before World War I, and rose to positions of authority thereafter. In the 1930s, a still common reaction of many industrialists among larger firms was that chemical engineers were a hybrid breed fit only for smaller manufacturing units which could not afford better.[46] ICI was a major disappointment. After its government-inspired formation in the mid 1920s, ICI dominated the highly rationalized business of chemical manufacturing in Britain; it took over a number of firms, such as the British Dyestuffs Corporation, that had shown signs of recognizing the potential of the chemical engineer.[47] Throughout the 1930s, ICI felt little need to employ academically-trained chemical engineers. Its technically important high pressure plant at Billingham was designed, built and operated by using a typically German division of labour between chemists and engineers. In the period 1928-38, the company employed only 16 per cent of the 159 chemical engineers turned out by University College, London, which ran the largest programme in Britain between the world wars. Only in the late 1940s did the company welcome chemical engineers in some of its divisions; and until the late 1950s, few chemical engineers were employed at Billingham.[48]

Nor were all educators convinced of the value of a training in chemical engineering. Professors of chemistry were in a powerful position within many British universities, and they were understandably reluctant to allow the founding of courses that might reduce recruitment to their own programmes. Even among those chemists and other academics who thought that more should be done to provide a training tailored to industrial skills, there was continued unease over whether the unit operations provided a scientifically rigorous enough set of general principles upon which instruction could be based.[49] But we need to relate this point more closely to the kind of tasks to which the

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[46] Lord McGowan, *Proceedings of the Chemical Engineering Group (Society of Chemical Industry)*, **25** (1943), 27.

[47] W.J. Reader, *Imperial Chemical Industries: A History* (London: Oxford University Press, 1970), vol. 2, pp. 249-257, 268-270, 354-363; "Firms employing former students. . . between July 1928 and July 1937," archives of University College, London (UCL) (1937), 32/3/3; "Report on the Department of Chemical Engineering, 1937-38," UCL (1938-1939), 32.

[48] John A. Oriel, "The chemical engineer in plant operation and management," *Chemical Engineer* (April 1955), xxxviii-xlii; R.H. Simpson, "The chemical engineer in a medium sized chemical company," *Chemical Engineer* (October 1960), A45-A49; Ronald Holroyd, "The acceleration of progress in the chemical industry due to activities during the second world war," *Chemistry and Industry* (June 14, 1969), 766-770; P.W. Reynolds, "Chemical engineering with ICI in Billingham," *Chemical Engineer* (March 1965), CE55-CE56.

[49] Donnelly, op. cit. (5), p. 588; Cohen, op. cit. (5), pp. 175-186.

majority of chemical engineers could expect to be assigned in industry. Most were probably destined for jobs in the management or operation of chemical plant, not its design or construction. Although the IChemE said that a training in plant and process design was of great value for would-be manufacturing chemists, the various derivatives of chemistry, such as applied chemistry, industrial chemistry and chemical technology, provided alternative ways of conceptualizing these tasks. For much of the period between the wars, Imperial College was split by these two competing perspectives on how best to train chemists for industrial jobs; either through the medium of the unit operations, or as a body of knowledge best imparted as separate industrial specialities. The University of Leeds also opted for the latter interpretation.[50]

Conclusions

Intellectual abstractions evolved along with a professional identity for chemical engineering and the expansion of the heavy chemical industry in Britain. The defining concept for the emerging profession, at least in Britain and the USA, was a set of largely empirical categorizations collectively known as "unit operations." The origins of the concept appear to have had distinct national origins. In the USA, unit operations have been postulated as an outcome of the Taylorist programme in manufacturing, or as a consequence of American enthusiasm for mechanical innovation and large-scale manufacturing. The unit operation, as first coherently articulated by A.D. Little, was defined as an isolable physico-chemical stage in a manufacturing process.

In Britain, by contrast, unit operations initially were popularized as plant-based chemical operations rather than the manufacturing processes per se; that is, the notion of chemical stages was reified in mechanical equipment. The adoption of this intellectual principle was initiated by professional consultants such as G.E. Davis from the 1880s and eventually taken up by academics and professional societies, particularly after World War I. The reasons for the adoption are various: thus for consultants, the concept provided a technical vocabulary for discussing plant design in operational terms without divulging company secrets; while for academics, unit operations generalized and organized the particularities of chemical plant design into a manageable curriculum.

The appropriation of the unit operation and other intellectual constructs as unique features of chemical engineering helped to consolidate the profession and to explicate its works to its clients, to the wider public, and to practising engineers themselves.

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[50] Donnelly, op. cit. (5), p. 580.