

PRODUCT INNOVATION AND THE GROWTH OF THE LARGE FIRM: THE CASE OF AIR LIQUIDE, 1902-1930

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ABSTRACT

This paper traces the early development of Air Liquide, the world's largest producer of industrial gases. By illustrating the dynamism of French industrial capitalism in the early twentieth century, the Air Liquide story calls into question the image of the French as also-rans in the Second Industrial Revolution. The story of Air Liquide also shows that geographical expansion and product diversification do not always lead to adoption of the multidivisional form (as in the case of Du Pont). Instead, Air Liquide remained a relatively small corporation at the center of a cluster of related firms. This paper suggests that the timing of product diversification may explain the differing organizational histories of Air Liquide and Du Pont.

Founded in 1902 by a group of French scientists and engineers to commercialize a new process for air liquefaction, Air Liquide quickly became a major player in the emerging field of industrial gases and has continued to develop and expand ever since. Today, Air Liquide operates seven research centers, 550 production facilities, and 6600 kilometers of gas ducts in 59 countries on five continents and is the world's largest producer of industrial gases, with a 20 percent share of the world market.¹

This paper examines the formative years of Air Liquide, from the company's founding to the eve of the Great Depression. This story is important in itself, as a major chapter in the history of the modern chemical industry, but it also has implications for assessing French industrial performance in the early twentieth century and for understanding the development of large corporations. To appreciate these larger implications of the Air Liquide story, one must first consider the historiographical background.

I. The Historiographical Context

Economic and business historians have long accepted that, at three crucial points in the past two centuries, France failed to take the path of economic modernization. In the early nineteenth century (so the story goes), France did not have an Industrial Revolution like Britain's. Then, at the end of the nineteenth century, France missed out on the Second Industrial Revolution that propelled Germany and the United States to world economic leadership. Finally, in the twentieth century, France has largely been a non-participant in the rise of large-scale industrial enterprise. The only thing that has changed in this accepted wisdom over the years is how historians explain—or excuse—these ap-

parent developmental failures.²

In the 1950s and 1960s, when the French themselves were writing little economic and business history, the Americans set the tone by attributing France's apparent backwardness to the cautious "malthusian" mentalities of its businessmen. In other words, it was a matter of entrepreneurial failure.³ Since the 1970s, the French have become increasingly interested in their own business history, and not surprisingly they have rejected the Americans' negative judgment of French entrepreneurship. At the same time, they have largely perpetuated the notion of French economic exceptionalism. Because of economic and institutional constraints beyond anyone's control, they argue, French business has followed a different path from that of the Germans or Americans, but not necessarily an inferior path.⁴ However, it is this notion of a "different path" that my work is beginning to call into question. Increasingly I am convinced that French industrial capitalism should not be viewed as deficient or inferior in the nineteenth and twentieth centuries precisely because it has differed so little from the industrial capitalism found in the other "developed" countries. That is, the French have been much more successful in developing high-tech, large-scale managerial enterprises than usually thought, with Air Liquide being a case in point.⁵

To invoke the case of Air Liquide in arguing against French exceptionalism requires one to look at the company's development in the larger context of the history of the chemical industry in the twentieth century. For this we can turn to the touchstone of comparative industrial history, Alfred Chandler's *Scale and Scope*. For Chandler, the dominant theme in the development of the chemical industry in the twentieth century is growth through product diversification, and the archetypal embodiment of this theme is Du Pont. Between 1902 and 1917, Du Pont consolidated its position as the leading manufacturer of gunpowder and explosives in the United States through a strategy of horizontal and vertical integration. Then, in order to find profitable places to invest its war profits and to utilize excess manufacturing capacity in the wake of World War I, Du Pont shifted from the large-scale production and marketing of a narrow range of standardized products to a strategy of developing and marketing a wide array of chemical products—everything from dyes, paints, plastics, and fibers to synthetic nitrogen and ammonia. Implementing this new strategy necessitated the complete reorganization of the company on the basis of the multidivisional model. But this strategy was so successful, argues Chandler, that it set the pattern of industrial development not only for the whole American chemical industry but eventually for almost all leading industrial enterprises in the United States and elsewhere after World War II.⁶ To what extent did Air Liquide follow this presumably normal or optimal path of development? Before that question can be answered, it is necessary to examine the company's founding and early history.

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II. The Founding of Air Liquide

At the end of the nineteenth century, Paris was not only a center for the arts but also a center for pure and applied scientific research, for the manufacture of instruments and precision tools, and for banking and venture capitalism. As such, it became an incubator for technological innovation and for the formation of high-tech start-up companies, not unlike what Boston/Cambridge and Silicon Valley would become in the United States in the late twentieth century. In particular, in the 1890s Paris played host to the loose, informal network of academic scientists and professional engineers who founded Air Liquide, most of whom were associated with France's fledgling electrical industry. This group included:

— **Arsène d'Arsonval**, professor of medicine at the Collège de France and a pioneer in electrophysiology, who made improvements in the Bell telephone receiver and founded a leading popular science magazine, *Lumière électrique*,⁷

— **Hippolyte Fontaine**, a skilled woodworker who began designing railroad carriages in the 1850s, rose to production chief at the Cail Railway Equipment Company, founded and long directed the influential *Revue industrielle*, became an expert on dynamos and electric motors as an associate of Zenobe Gramme, and served as president of the Société internationale des électriciens,⁸

— **B. Abdank-Abakanowicz**, a Lettish engineer who ran and perhaps owned the Laboratoire Volta outside of Paris, served on the board of the Compagnie des Compteurs, and participated in the founding of the French Thomson-Houston Company in 1893,⁹

— **The Le Chateliers**, a remarkable family of engineers and scientists which included Henry Le Chatelier, professor of applied chemistry at the Ecole des Mines and the Collège de France, and his younger brother, André, a metallurgical scientist with the naval engineering service (Génie maritime), both of whom would serve as directors of Air Liquide and its subsidiaries.¹⁰

The central figure in the birth of Air Liquide, however, was Georges Claude. Claude is arguably France's leading industrial scientist of the past hundred years, but he is conspicuously absent from the authoritative *Dictionnaire de biographie française* and most French encyclopedias. This absence surely derives from his outspoken support for collaboration with Nazi Germany during the Occupation for which he was tried and convicted of treason in 1945. After serving five years in prison, Claude lived out his life in poverty and obscurity, dying in 1960.¹¹

Georges Claude was born in Paris in 1870. His father had invented a machine to fold and package tissue papers for pastry shops, which gave him sufficient income to retire early and devote himself to his son's education. In 1886 Georges entered the recently opened Ecole de Physique et de Chimie de Paris (EPCI), which was already emerging as a center for applied physics and chemistry and for the study and application

of electricity (its most notable faculty member was Pierre Curie). In 1889, Claude graduated with a degree in electrical engineering and went to work for a small electrical testing company in Paris. At the same time he started writing for Arsonval's *Lumière électrique* and other science magazines, which led to the publication of a bestseller, *L'Électricité à la portée de tout le monde*, in 1901. By then, Claude had also met Abdank-Abakanowicz, who hired him for the new Thomson-Houston Company, where he worked throughout the 1890s (his "day job") while he undertook the researches that ultimately made his fame and fortune.¹²

In 1892, Henri Moissan, who had earlier invented the electric furnace that produced calcium carbide, discovered how to generate acetylene by dissolving calcium carbide in water. In 1895, Henri Le Chatelier demonstrated that a mixture of acetylene and pure oxygen produced the hottest and brightest flame yet known to man. Le Chatelier and his associates (who included Abdank) immediately set out to manufacture acetylene in commercial quantities, but they were stymied by acetylene's annoying habit of exploding spontaneously when stored in steel tanks. So they brought in Claude to find a way to stabilize and store acetylene. He did this by dissolving acetylene in acetone and then combining this solution with charcoal (following the model of Alfred Nobel, who stabilized nitroglycerine by combining it with kieselguhr). To bring Claude's system to market, the *Compagnie française de l'acétylène dissous* was founded in 1896, with Hippolyte Fontaine as president and with Abdank, Le Chatelier, and Arsonval as directors.¹³

Initially everyone thought the market for acetylene would be in mobile lighting systems for trains and road vehicles, but the invention of the oxyacetylene welding torch opened a potentially much larger market for acetylene, provided that a cheap source of oxygen—and a convenient way to store it—could be found. To this end a "société en participation" was formed in 1899 to support Claude's search for a commercially viable method of liquifying air and separating it into liquid oxygen and liquid nitrogen. Leading this effort was Paul Delorme, a former classmate of Claude's at the EPCI and a fellow engineer for Thomson-Houston.

With this backing, Claude set about his research, after hours and on weekends, using the compressed air machines available at the workshops of various Paris tramway companies controlled by Thomson-Houston.¹⁴ His work consumed three years and required his backers to raise their investment from an initial 10,000 francs to 50,000 francs by 1902. Ultimately, Claude was beaten to the punch by the German pioneer in refrigeration and ice-making technology, Carl von Linde, who succeeded in liquifying air on a commercial scale in 1901. Linde's system, which involved the single expansion of compressed air through a needle valve, was successfully commercialized in the United States by the Linde Air Products Company, later a part of Union Carbide. Meanwhile, Claude persevered along a different path, what he called "expansion with external work with recuperation," that promised to produce liquid air more economically once Claude found a method of lubricating a moving piston at low temperatures. Discovery of that lubricant in petroleum ether allowed Claude to demonstrate his system successfully on

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May 26, 1902 (a day before his backers planned to meet to dissolve their partnership). By the end of June 1902, when Arsonval reported on Claude's work to the Académie des sciences, Claude had a working apparatus that could produce twenty-five pounds of liquid air per hour.¹⁵

Delorme and the other backers were sufficiently convinced of the practicality of Claude's air liquefaction method—and its superiority to the Linde method—that in the fall of 1902 they founded a joint-stock company, Air Liquide, with Delorme as president, to develop and exploit the Claude process.¹⁶ Meanwhile, Claude proceeded to the next phase of research, designing a machine to separate liquid air into oxygen and nitrogen. This work consumed two years and required the company to raise its investment from an initial 100,000 francs to 500,000 francs, but by 1904 Claude had developed a separation system that offered significant efficiencies over the comparable Linde system that had been on the market since 1902.

As Claude continued his research in 1902-04, Air Liquide laid the foundations of the oxyacetylene welding industry in cooperation with the Compagnie française de l'acétylène dissous. By June 1903, Air Liquide had opened its first air liquefaction plant at Boulogne-sur-Seine, adjacent to Claude's laboratory. That same year André Le Chatelier, with support from Marseille shipping interests, founded the Société d'acétylène dissous du Sud-est to exploit the Claude process in the south of France and to develop the technology and equipment for steel welding (primarily for the underwater repair of steamships). In 1904, Air Liquide launched the Compagnie des Gaz Comprimés to make canisters for storing and shipping industrial gases and to produce oxygen at a plant in Lyon. By 1907, profits from oxygen production and related operations were sufficient for Air Liquide to declare its first dividend. As the author of the company's fiftieth anniversary retrospective put it, "it had thus taken eight years of continuous effort and patience to put into practice and render industrially viable the processes of a new industry [that was] considered at its outset so adventuresome both in the audacity of its technology and in the difficulties of execution that it presented."¹⁷

III. The Making of an Industrial Group, 1906-1914

Between 1906 and 1913, the nominal capital of Air Liquide rose from one million francs to eleven million, and its assets increased even more, from 614,000 francs to over 23 million, making Air Liquide France's eighth largest chemical company and its seventy-sixth largest publicly-held industrial enterprise on the eve of World War I.¹⁸ This rapid growth reflected progress on three fronts: 1) perfection of the technology and development of nationwide production in Air Liquide's core businesses (industrial gas and welding equipment), 2) implantation of these businesses outside of France, and 3) development of additional products and processes. These years also witnessed the emergence of an approach to organizational development that would distinguish Air Liquide's

entire history: undertaking initial geographical expansion or product diversification by means of joint ventures or legally separate subsidiaries and later absorbing the most successful of these into the mother company while at the same time continuing to operate in related fields (e.g., acetylene production and welding services) through "sister" companies in which Air Liquide participated financially and shared top management. In effect, Air Liquide was creating an industrial group.

Developing the Core Businesses. Between 1906 and 1913, Georges Claude continued to improve and refine his processes for air liquefaction and the separation of liquid oxygen and nitrogen. These refinements were incorporated in a line of compact, highly efficient machines that could produce 5-20 m³ of oxygen per hour and up to 400 m³ of nitrogen per hour at 99.7 percent purity. With these machines, Air Liquide manufactured and bottled gas at six plants in France. The company then marketed this gas through its subsidiary, Gaz Comprimé. Air Liquide also furnished machines to foreign subsidiaries and independent gas producers.¹⁹ Meanwhile, the production of acetylene remained the purview of Air Liquide's sister companies, Acétylène Dissous and Acétylène Dissous du Sud-est.²⁰ In 1909 the creation of yet another sister company, Soudure Autogène Française, headed by André Le Chatelier, consolidated the welding services end of the business.

Geographical Expansion. From its inception, Air Liquide had multinational aspirations. Realizing that their proprietary technology had few rivals worldwide, Delorme and company moved quickly into foreign markets in the years before World War I. In Europe, this entailed the creation of wholly-owned or majority-owned subsidiaries, starting with Air Liquide Belge in 1906 and followed by Aira Liquida Italiana in 1909, and the signing of licensing agreements with firms in England, Germany, Austria, Russia, Spain, Sweden, Greece, and Turkey (with Air Liquide often holding a financial stake in its licensee). Beyond Europe, Air Liquide founded a Canadian subsidiary in 1910 and, in tandem with the east Asian operations of Acetylene Dissous du Sud-est (see note 20), it launched the Groupe Air Liquide en Extrême-Orient with a plant in Saigon in 1910 and one in a suburb of Kobé in 1911 to serve the fast-growing Japanese shipping industry.²¹

In 1914-15, Air Liquide moved to establish a presence in the United States, the world's largest market for oxyacetylene welding. Already, in the early 1900s, a Frenchman, Eugene Bournonville, had brought the dissolved acetylene process to the United States and had formed with Augustine Davis, a pioneer in acetylene production, the Davis-Bournonville Company to manufacture acetylene generators and welding apparatus. However, the production of liquid oxygen was being pursued mainly by the American Oxygen Company (owned in part by Percy Rockefeller, a nephew of John D.) using chemical methods. In 1911 American Oxygen started to experiment with producing oxygen from air at its plant in Philadelphia, but it had had little success by 1914 when Air Liquide dispatched W. T. P. Hollingsworth to propose a joint venture. The result was the founding of the Air Reduction Company, which moved rapidly to integrate all as-

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pects of oxyacetylene production, absorbing the Davis-Bournonville Company in the process. By the early 1920s Air Reduction had emerged as one of the two prime movers in the American industrial gas industry along with Union Carbide.²²

Product Diversification. Although Air Liquide focused mainly on its core businesses in the pre-World War I years, it also took early steps toward product and process diversification, reflecting the broad interests and technical versatility of Georges Claude and his associates. By 1912, the company had entered the refrigeration equipment business with contracts to equip the refrigerator ships of two leading French steamship companies, Chargeurs Réunis and the Compagnie Générale Transatlantique. It also participated in a joint venture with a Belgian company, Société d'Ougrée-Marahaye, to utilize liquid oxygen in the smelting of pig iron. At its Lyon plant, Air Liquide began producing hydrogen peroxide, much in demand as a bleaching agent and antiseptic. The company also encouraged and financed Georges Claude's research on the industrial production of rare gases, mainly neon and argon. This research led to the invention of neon lighting, which created a sensation in 1910 when it was first used to illuminate the facade of the Grand Palais for the Paris Auto Show.²³

Defining an Organizational Style. Throughout these early years, the organizational structure of Air Liquide remained somewhat open-ended as the company pursued its various initiatives via a complex array of subsidiaries, joint ventures, "participations," and licensing agreements. But in order to tighten control of its increasingly far-flung interests, Air Liquide undertook the first of what would become periodic rounds of consolidation in 1911-12 when it absorbed its two largest foreign subsidiaries, Air Liquide Belge and Aira Liquida Italiana, along with Gaz Comprimé and another subsidiary, the Société pour l'utilisation de l'air et ses dérivés. Air Liquide also tightened its relationship with Acétylène Dissous through a stock purchase. These moves established a pattern of organizational development that embodied what the author of the fiftieth anniversary retrospective volume called "one of the essential principles of Air Liquide's financial policy:"

Never wishing to engage the company's own capital in operations that entailed certain risks, [Air Liquide] has always preferred to divide these risks by constituting separate companies which could then be called upon to prove themselves. Only after years of experience would these companies and their capital be judged ready to be incorporated into the mother-company itself.²⁴

In other words, pursue all technical and commercial options, but do not risk the financial security of the core business until the new ventures have proven themselves.

IV. Expansion and Maturation, 1914-1930

After the initial disruption of its operations by the mobilization of August 1914, Air Liquide came to benefit greatly from the First World War as demand burgeoned for the oxygen and nitrogen used in the manufacture of war matériel (nitrogen-based explosives)

and hospital supplies (hydrogen peroxide). Accordingly, Air Liquide quadrupled the size of its Boulogne-sur-Seine plant and built three additional plants for industrial gases. It also started producing liquid chlorine (for poison gas) at Grande-Paroisse, on the Seine southeast of Paris, in a plant that the French government had recently sequestered from the German pharmaceutical company, Merck.²⁵

Although it came out of the war with greatly increased manufacturing capacity, Air Liquide did not suffer from the overcapacity that plagued many other war suppliers and that made retrenchment and cartellization a central theme of the postwar history of the chemical industry. On the contrary, the continued growth of oxyacetylene welding and the proliferating industrial applications of oxygen and nitrogen seemed to render Air Liquide recession-proof in the 1920s. As the analyst for the *Crédit Lyonnais* observed in 1918, “the extension of [Air Liquide’s] business and the success that it has achieved have created a privileged situation relative to its competitors not only in France but also abroad.”²⁶

Air Liquide continued to expand its core businesses in the early 1920s. This led to a second round of mergers and consolidation in 1923, the most important being the absorption of *Acétylène Dissous*.²⁷ The company also continued to pursue the strategy of new product development first adopted before 1914. Air Liquide’s biggest “new” product by far in the 1920s was synthetic ammonia. Working at his laboratory at Grande-Paroisse in 1917, George Claude had developed an alternative to the Haber process for the synthesis of ammonia from nitrogen and hydrogen gas. To exploit this new Claude process, Air Liquide launched the *Société Chimique de la Grande-Paroisse* (SCGP) in 1918 as a fifty-fifty joint venture with Saint-Gobain. Encouraged by the initial results, the two partners decided in 1919 to bring ammonia production at Grande-Paroisse up to a world-class scale, necessitating an increase in SCGP’s capital from 14 to 34 million francs. They also moved into the American market with the founding of *Lazote Inc.*, a joint venture between SCGP and Du Pont.²⁸

By the end of the 1920s, Air Liquide’s social capital had risen to 88 million francs and its assets amounted to more than 500 million francs, making it France’s fourth largest chemical company and placing it among France’s top 25 publicly-held industrial enterprises.²⁹ The company’s annual reports for 1929 and 1930 provide a snapshot of where the company stood at the end of its crucial first quarter century of development and on the eve of the Great Depression:³⁰

— By 1930 Air Liquide was operating 32 oxygen plants and 26 acetylene plants in France, and new plants were under construction at Grenoble, Le Mans, Caen, and Charleville,

— Air Liquide’s Champigny plant (formerly part of *Acétylène Dissous*) remained a leading developer and manufacturer of welding equipment,

— Air Liquide’s subsidiaries in Canada, Belgium, Japan, and North Africa continued to expand, with new plants coming on line in Casablanca and Dakar, and the company was moving into Southeast Europe through a new

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subsidiary, Société Orientale de l'Oxygène et d'Acétylène,

— Air Liquide was strengthening its position in Germany by licensing the Claude ammonia process to Kali Industries,

— the Far East group continued to expand, with new facilities opening in Bangkok, Haiphong, and Shanghai,

— a recent agreement with Du Pont had exchanged Air Liquide's shares in Lazote for shares in Du Pont, and Du Pont continued to license the Claude ammonia process.

Finally, 1930 witnessed Air Liquide's participation in the founding of Claude Lumière to more effectively exploit Georges Claude's patents in neon lighting, which strengthened the company's stake in yet another high-tech growth area and helped sustain it through the ups and downs of the Great Depression.

V. Toward a Comparative Perspective: Air Liquide Versus Du Pont

Placed in the historiographical contexts with which this essay began, the story of Air Liquide gives credence to the optimistic interpretation of French industrial development and to the notion that France was a major participant in the Second Industrial Revolution. Indeed, to the two French "first movers" that Alfred Chandler acknowledged in *Scale and Scope* (Saint-Gobain in flat glass and Michelin in tire and rubber),³¹ we can now add a third, Air Liquide in industrial gases.

But the more difficult question remains: to what extent did the French achieve their success by following the same strategies of technological and organizational development found in the other leading industrial countries? Or, to be more specific, to what extent did Air Liquide's development mimic or mirror the dominant pattern of development in the American chemical industry exemplified by Du Pont?

Air Liquide and Du Pont differed in obvious ways. In 1902, when the former was just getting started, the latter, through its consolidation of powder production in the United States, had already become one of the largest industrial corporations in the world. And the discrepancy in size persisted: as of 1930, Du Pont had assets over thirty times those of Air Liquide.³² Yet, since 1918, the growth of both companies had depended substantially on the development of new products. As related by Hounshell and Smith, Du Pont's strategy of product diversification unfolded in two stages: in the immediate aftermath of World War I, a cash-rich Du Pont bought its way into a number of new product areas, either by taking over the companies that developed them (e.g. Roessler & Hasslacher) or by purchasing patents and technology (from the French it got not only the Claude ammonia process but also artificial silk and cellophane). From the late 1920s, Du Pont shifted to in-house development of new products through the expansion of the Du Pont Labs.³³

Air Liquide lacked the financial resources to buy technology as Du Pont did or to undertake basic research on the scale of the Du Pont Labs. Still, it got amazing mileage

out of the inventiveness of one man, Georges Claude, to the extent that product and process development remained a key part of the company's growth strategy. In other words, once allowance is made for the gross discrepancy in size and resources, the developmental arc traced by Air Liquide proved to be quite similar to that of the leading chemical firms elsewhere.

Where Air Liquide did not follow suit was in corporate restructuring. For Chandler, the climax of the Du Pont story in the interwar years was the consolidation and continued promotion of multiple product lines via adoption of the multidivisional model of organization. By contrast, Air Liquide had not yet adopted the M-form structure at the outbreak of World War II. What it had done instead was to cluster its main operations under a centralized managerial hierarchy, through the mergers of 1911-12 and 1923, while leaving other operations in separate, quasi-independent companies. Thus Air Liquide remained a relatively small company at the center of an industrial group, rather than becoming an American-style integrated industrial corporation.

Why did Air Liquide not follow Du Pont's organizational lead? There are many possible explanations. Some historians would undoubtedly point to the great differences in the economic and institutional circumstances in France and America and to the particular problems in financing industrial ventures in twentieth century France.³⁴ But the evidence presented here seems to favor a more "internalist" explanation that focuses on the chronology of the two firms' development.

A comparison of the experiences of Air Liquide and Du Pont suggests that organizational structure depends not only on what growth strategy a particular company pursues but also on *when* in its life cycle the company implements it. A firm undertaking geographical expansion and product diversification late, after already developing large-scale production capacity and extensive marketing structures to produce and distribute a single standardized product in a national market (as Du Pont had done with gunpowder up to 1918), may find that the proper organizational response is to convert its centralized functional structure to a decentralized multidivisional structure. However, if a firm undertakes product diversification and multinational marketing from its inception, as Air Liquide did, then creating separate but related firms (via licensing, joint ventures, etc.) may be the best method of organizational expansion because it allows the mother company to avoid premature encumbrance with a large and costly managerial hierarchy and allows it to pursue new opportunities in a rapidly evolving technology more expeditiously. Having initially succeeded with such an organizational system, a company may then be reluctant to adopt a more centralized structure, even of the multidivisional variety, except in those product lines where economies of scale are possible.

So perhaps the lesson of Air Liquide's early development is that the multidivisional form, once hailed as the necessary and universal model for the management of modern industrial enterprises, mainly serves the needs of the late-diversifying mass producer and is less useful or even unnecessary for the early-diversifier.

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NOTES

1. Jean-Michel Béhar, *Guide des grandes entreprises* (Paris: Seuil, 1995), 44-49.
2. For a review of the literature, see Colin Heywood, *The Development of the French Economy, 1750-1914* (Cambridge: Cambridge University Press, 1992).
3. See particularly the early work of David Landes: "French Entrepreneurship and Industrial Growth in the Nineteenth Century," *Journal of Economic History*, 9, no. 1 (May 1949), 45-61, and "French Business and Businessmen," in E. M. Earle, ed., *Modern France* (Princeton: Princeton University Press, 1951). See also the critical review of the literature in Charles P. Kindleberger, *Economic Growth in France and Britain, 1851-1950* (Cambridge MA: Harvard University Press, 1964), 88-134.
4. See Maurice Lévy-Leboyer, "Innovation and Business Strategies in Nineteenth and Twentieth Century France," in Edward C. Carter, et al., eds., *Enterprise and Entrepreneurs in nineteenth and Twentieth Century France* (Baltimore: Johns Hopkins University Press, 1976), 87-136, and "The Large Corporation in Modern France," in Alfred D. Chandler, Jr., and Herman Daems, eds., *Managerial Hierarchies* (Cambridge MA: Harvard University Press, 1980), 117-160; Patrick Fridenson and André Straus, eds., *Le Capitalisme français, 19e-20e siècles: Blocages et dynamismes d'une croissance* (Paris: Fayard, 1987); and François Caron, "Entreprise," in Pierra Nora, ed., *Les lieux de mémoire*, t. III, pt. 2 (Paris: Gallimard, 1992), 323-375.
5. See my "The Beginnings of Big Business in France, 1880-1920: A Chandlerian Perspective," in *Essays in Economic and Business History*, 11 (1993), 1-24; "The Emergence of Managerial Capitalism in France, 1880-1930: Three Case Studies," in *Essays in Economic and Business History*, 13 (1995), 41-53; and "Putting France in the Chandlerian Framework: France's 100 Largest Industrial Firms in 1913," *Business History Review* 72, no. 1 (Spring 1998), 46-85.
6. Alfred D. Chandler, Jr. *Scale and Scope: The Dynamics of Industrial Capitalism* (Cambridge MA: Harvard University Press, 1990), 170-193. As Chandler puts it, "this strategy of growth was the most sophisticated one to evolve among industrial firms before World War II, ...was widely adopted in the years following the war, and...was central to the intensification of competition that brought underlying changes in the strategy and structure of large American industrial firms in the 1960s" (181-182).
7. François Caron and Fabienne Cardot, dirs., *Histoire générale de l'électricité en France*, I (Paris: Fayard, 1991), 48-49.
8. *Dictionnaire de biographie française* (Paris: Letouzey et Ainé, 1933-), XIV, 290-91; M. Magnien, "Un inventeur, un administrateur: Hippolyte Fontaine, la vie d'un électricien au tournant du siècle," *Bulletin d'histoire de l'électricité* 4 (1984), 5-29.
9. Georges Claude, *Ma vie et mes inventions* (Paris: Plon, 1957), chapter 5.
10. Their father, Louis Le Chatelier, a state engineer, set up the technical services of the Chemin de fer du Nord and, along with Henri Saint Claire Deville and Henri Merle, founded the French aluminum industry. See François Le Chatelier, *Louis Le Chatelier (1815-1873), Elisabeth Durand (1827-1902), leurs ascendants, leurs descendants* (Nancy: Imprimerie Rubrecht, 1973).
11. Claude was accused of helping the Germans with the V-1 and V-2 rockets, but he adamantly denied this, and that charge was dropped before his trial. Convicted of treason "with extenuating circumstances" (because of his record of service in World War I), he escaped execution, but he was stripped of membership in the Académie des sciences and other academic honors. See Maurice Ribet, *Le procès de Georges Claude* (Paris: Jean Vigneau, 1946), and Claude's self-justifying but generally factual autobiography, *Ma vie et mes inventions* (see note 9).
12. In *Les Patrons sous l'Occupation* (Paris: Editions Odile Jacob, 1995), Renaud de Rochebrune and Jean-Claude Hazera discuss the Claude case (250-254), and they explain how the directors of Air Liquide avoided official retribution after the war for Claude's high-profile collaboration by playing a double game, maintaining ties with both the Vichy government of Marshal Pétain and the Free French organization of General de Gaulle in 1940-1944 (254-259).
13. Claude, *Ma vie*, 4-30.
14. Claude, *Ma vie*, chapter 5; Le Chatelier, 157-169.
15. Thinking that liquid oxygen would replace calcium carbide as the key ingredient in manufacturing

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acetylene (which never happened), Claude had actually begun working on the liquefaction of air as early as 1896 (*Ma vie*, 39).

15. As Claude later described it in *Liquid Air, Oxygen, Nitrogen* (London: J & A Churchill, 1913), the major feature of his system was the production of mechanical work from the expansion (and liquefaction) of air that could then be re-cycled in the air compression stage: "this recuperated mechanical work may be utilized in diminution of the work of compressing the air so that the advantage of extracting from the compressed air the maximum of work, by means of the type of liquefaction under pressure,... acts in a certain way as if it were raised to the square, since both the cold produced and the energy recuperated are increased at one and the same time" (178).

16. Delorme remained Président Directeur-Général of Air Liquide until 1945 when he was succeeded by his son, Jean Delorme, who headed the firm until 1967.

17. *Cinquantenaire de la Société L'Air Liquide, octobre 1902-octobre 1952* (Paris: Imprimerie Jeanrot, 1952), 14. This privately printed volume is found in Archives Nationales [hereafter AN], 65 AQ P4¹. The preceding account of the company's founding as well as the account of the company's subsequent history below relies heavily on this source (all translations from the French are mine).

18. These rankings are from Smith, "Putting France in the Chandlerian Framework," 57.

19. The principal use for liquid oxygen was in oxyacetylene welding. The Claude oxygen machines were smaller than the Linde machines and served the needs of small-to-middle size welding businesses. Liquid nitrogen was used mainly for the production of cyanamide fertilizers. For a description of the Claude machines, see Claude, *Liquid Air*, 401ff.

20. In addition to producing acetylene in southern France, Acétylène Dissous du Sud-est developed and marketed welding equipment, especially for shipbuilding and repair, and set up repair facilities adjacent to the shipyards of Marseille, and also in the port of Saigon to serve the shipyards of Messageries Maritimes through a joint subsidiary with Air Liquide, the Société d'Oxygène et d'Acétylène d'Extrême Orient. See *Cinquantenaire* in AN 65 AQ P4¹.

21. See the 1913 report in the Crédit Lyonnais Archives, Etudes financières [hereafter CLEF], DEEF 30212, 3937, and the March 1962 issue of *La Cryogène* in AN 65 AQ P4².

22. See William Haynes, *The American Chemical Industry*, VI (New York: Van Nostrand, 1949), 5-8. The details of Air Liquide's involvement in the Air Reduction Company are sketchy. All officers of Air Reduction Company were Americans, but Air Liquide documents imply that it was represented on the board. Confidential reports in the Crédit Lyonnais files indicate that Air Liquide continued to have a significant financial stake in Air Reduction through the 1920s, and Air Liquide's 1930 annual report, in a section devoted to international operations, noted that Air Reduction was "in excellent condition."

23. The Claude Neon Lighting Company, in which Air Liquide participated, became a leader in electrical signage. See Claude, *Ma vie*, chapter 7, and Wiebe E. Bijker, *Of Bicycles, Bakelite, and Bulbs: Toward a Theory of Sociotechnical Change* (Cambridge MA: MIT Press, 1995), 213-18.

24. *Cinquantenaire*, in AN 65 AQ P4¹.

25. Rochebrune and Hazera, 251.

26. "Projet d'émission de bons," 10 mai 1918, CLEF, DEEF 30212, 3937-2.

27. Acétylène Dissous du Sud-est remained nominally independent, but at the death of its founder, André Le Chatelier, in 1929 it too was merged into Air Liquide.

28. On Lazote, see David A. Hounshell and John Kenly Smith Jr., *Science and Corporate Strategy: Du Pont R & D, 1902-1980* (Cambridge: Cambridge University Press, 1988), 183-189.

29. Based on the rankings of French companies in 1936 presented by Bruce Kogut in his 1997 unpublished paper, "Evolution of the Large Firm in France in Comparative Perspective." I wish to thank Professor Kogut for making this work available to me.

30. *Assemblées Générales*, 1929, pp. 846-50; 1930, pp. 1044-48.

31. Chandler, *Scale and Scope*, 106, 445, 452.

32. Based on Chandler's figures in *Scale and Scope*, 646, and converting Air Liquide's assets to US dollars at a rate of 25.52FF/\$ based on R. L. Bidwell, *Currency Conversion Tables* (London: Rex Collings Ltd, 1970).

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33. See Hounshell and Smith, part II, pp. 119-220. Chandler argues that most other large American chemical companies followed Du Pont's lead into product diversification by the 1930s, as did the British giant, Imperial Chemicals. However, the German companies, by then consolidated in I. G. Farben, largely eschewed new product development and instead spent the 1920s and 1930s recovering their prewar position in existing industries. *Scale and Scope*, 170-188, 358-366, 564-584.

34. This is the approach of Maurice Lévy-Leboyer in "The Large Corporation in Modern France" and in "La grande entreprise: un modèle français?" in M. Lévy-Leboyer and J-C Casanova, eds., *Entre l'Etat et le Marché: l'Economie française des années 1880 à nos jours* (Paris: NRF-Gallimard, 1991), 365-410.

