

Ludwig Mond

A Brilliant Chemical Engineer

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Resumen

Ludwig Mond (1839-1909) fue el primero en establecer el proceso Solvay para amoniaco-soda en Inglaterra y dedicó la mayor parte de su vida a perfeccionarlo. Fue un ingeniero de amplia visión que lo llevó a poner en práctica la mayor parte de sus descubrimientos, entre ellos el gas de agua y una planta de potencia de alta eficiencia, la preparación por primera vez de carbonilos metálicos y su utilización en la extracción directa del níquel de sus minerales. El imperio químico que fundó fue usado por su hijo Roberto para establecer ICI (Imperial Chemical Industries).

Abstract

Ludwig Mond (1839-1909) was the first to establish the Solvay ammonia soda process in England and spent most of his life perfecting it. An outstanding engineering vision led him to realize the multiple possibilities of his discoveries, among them the development of water gas and an efficient power gas plant, the first-time preparation of metal carbonyls, particularly nickel carbonyl and its utilization for extracting nickel directly from its ores. The chemical empire he created was used by his son Robert to establish ICI (Imperial Chemical Industries).

Life and career

Ludwig Mond was born in Cassel, Germany, on March 7, 1839, the second child of Meyer Bar (Moritz) (1811-1891) and Henriette Levinsohn. His elder brother died in infancy. The other children were Philippina, Adolf, Rudolf, and Mathilde. At the age of seventeen his father Meyer had moved from Ziegenhain, his village, to become an apprentice in Aaron Levinsohn's silk business in Cassel. He did well and after some time he married Levinsohn's youngest daughter Henrietta and the couple soon came to be trusted to run the business. The Mond family was moderately successful, a typical wealthy and cultured Jewish family. Ludwig's aunt, Johanna Levinsohn, was married to Adolf Löwenthal who initially had managed the Cologne agency for the electro-

plating and allied processes of the Royal Galvanoplastic Institute of Berlin and then opened a successful galvanoplastic plant in Cologne. Adolf was the first to stimulate Ludwig's scientific interest, by giving him on one occasion a galvanic battery, and in another an edition of Liebig's letters (Cohen, 1956).

Ludwig's entered the Realschule in Cassel at the age of nine and after graduation moved to the Cassel Polytechnic School. During his 2.5 years there he took courses on higher mathematics, physics, theoretical and technical chemistry, mineralogy and geology, botany and zoology, engineering, architecture, machinery, and mechanical drawing. At the same he acquired from his father's bookkeeper the necessary commercial knowledge to qualify for admission to the Cassel's Merchant Guild. In 1855, when he was 16.5 years old, he entered the University of Marburg as a student of chemistry. The director of the chemistry department was Hermann Kolbe (1818-1884). At the end of the summer of 1856 he moved to the University of Heidelberg carrying excellent letters of recommendation from Kolbe. There, Robert Wilhelm Bunsen (1811-1899), who had just joined the staff, was pleased with Kolbe's testimonial and accepted Ludwig immediately as a student. At Bunsen's laboratory he did research on improving the poor burning qualities of lignite and on the utilization of peat for industrial purposes (Cohen, 1956).

Ludwig enjoyed his studies at Heidelberg and found time for other activities. He became a reasonable violinist and had a good baritone voice. He was a skilled duellist and became marked by several scars, which he kept hidden below his large black beard (Roberts, 1989). By April 1858 at the age of 19 he concluded that he was educated enough and quit the university without a degree or any formal qualification. He was considered by his teachers to be a gifted pupil and apparently this type of self-planned education was not all that unusual. There were several reasons for his abandoning Heidelberg without taking his degree: He did not know Latin, an obligatory subject; he felt that a doctorate was not a requirement for the career he had in mind, and, in addition, he believed that chemical manufacturers at that time did not need doctors. The next reason was very important: during all his studies he was in deep debt and his father was always complaining about his excessive requests for money. He was fortunate that his uncles, Adolf and Johanna Löwenthal, helped supporting him at Heidelberg.

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After leaving Heildelberg he went to live in Cologne with his uncles and there he met and became very friendly with his cousin, Frida Löwenthal (1842-1923), with whom he became secretly engaged when she was only 13 years old and eventually married in 1866. Frida was to support him intellectually, socially, and physically throughout his life (Abel, 1989). While in Cologne Ludwig initiated his apprenticeship in his uncle's business; he was supposed to become a junior partner in the firm but this relation did not work and he abandoned after about three months. While working with his uncle he developed methods for utilizing the waste of the electrolytic bath to produce zinc sulfate and nitric acid (Cohen, 1956).

During the next eight years he moved from one job to another trying to find himself, but at the same time acquiring extensive experience in chemical manufacturing, especially of soda, ammonia, and acetic acid, in Germany, England, and Holland.

From Cologne, Ludwig joined a factory at Mombach, near Mainz, making acetic acid by the dry distillation of wood, and also wood tar and lead acetate. The factory was not a moneymaking business because it did not produce enough by-products. A former partner had been experimenting unsuccessfully in producing verdigris (copper acetates), which was needed as a pigment for printing textiles. Ludwig took over the challenge and in a few days he developed a manufacturing procedure, which was cheap and not harmful to the workmen's health. The owner of the factory was so impressed that he offered him a contract, which included a share of the profits and a guaranteed minimum salary on which he could comfortably live. In spite of these clear benefits, he moved to a similar factory, located at Hachenberg, Nassau, but again this job lasted for a very short time. Meanwhile he had been called into the army, but his father put up a large sum to buy him a substitute, a legal option to avoid conscription. Ludwig was now free to go wherever he chose (Cohen, 1956).

In June 1860, at 21 years of age, Ludwig was offered a job in a Leblanc soda works at Ringenkuhl. He started, almost accidentally, on what was to be the major part of his life's work: the production of one of the key chemicals required by so many branches of the rapidly developing heavy chemical industry. Sodium carbonate was an essential ingredient for three growing industries: it was used in the textile processing as an alkaline scour in the bleaching of linen and cotton cloths, in glassmaking as a fluxing ingredient to lower the melting point of soda lime glass compositions, and in soap-making. Cohen (Cohen, 1956) describes this period of Mond's life and outlines some of his schemes for profit improvement by raw material recovery. He would cost his processes on the base of a few laboratory experi-

ments, press on with the project and run into problems. He would then work night and day to solve them, which he would do, only to find that they were never quite as profitable as he had hoped (Roberts, 1989).

While at Ringenkuhl, Mond realized that one of the weaknesses of the economics of the Leblanc process was the large amount of black sludge or alkali waste, which contained all the original sulfur from the pyrites, and were thrown away. He began experimenting on ways of recuperating the sulfur until eventually he developed a process capable of recovering almost 50% of the sulfur in calcium sulfide by atmospheric oxidation, lixiviation, and subsequent separation of sulfur by treatment of the liquors with hydrogen chloride. This process was patented in Ludwig's name in France in 1861 and in England in August 1862 (Mond, 1862). His father agreed to pay for the registration in Germany, France, and England. He then left Ringenkuhl and moved to Ehrenfeld near Cologne, where a family friend by the name of Weil, was making some experiments on a semi-technical scale, for recovering ammonia and tar products from leather waste (Cohen, 1956).

He returned to his job at the factory in Ringenkuhl where the director had expressed his interest in testing Ludwig's process on a sufficient scale evaluating its economics potential. Afterwards he received an offer from the firm of Wede P. Smits & Zoon to erect a plant in Utrecht for the making of sulfur from pyrites (Cohen, 1956).

All this experience built his reputation as a clever chemical engineer, with a solid knowledge of application of scientific principles to a wide range of chemical processes.

On September 1862, when he was 23 years old, he moved to England where he believed he could put his patent on the recovery of sulfur into practice. At that time the British factories using the Leblanc process were producing more soda than the rest of Europe put together. Moritz Mond had some contacts in London and Manchester, which helped Ludwig meet with John Hutchinson (1825-1865), who in 1847 had set up the first Leblanc soda factory in Widnes and had become one of the largest producers of sodium carbonate. This meeting was crucial for Ludwig's future; it put him on the track that would lead him to become the most important chemical manufacturer in Britain and to become extremely rich. As a result of the meeting an agreement was reached by which Mond would work for John Hutchinson & Company not as their employee but as an independent though salaried scientist, free to sell the rights to his patent to any of his competitors. In return for installing his sulfur recovery process the firm would pay him £300 per year, provided Hutchinson & Co. should be able to make £450 per annum for it. The agreement led to continuous friction between Hutchinson and Mond (Roberts, 1869).

By February 1863 Mond had already modified his original process to a new one capable of extracting sulfur from the waste with far less cost in labour. It involved passing air through the waste while it was in the lixiviation vats. This obviated the labour of transferring it repeatedly from the vats to the hurdles for re-oxidation, which has been a costly feature of his earlier method. These modifications led to a new patent, which Mond registered the following autumn (Cohen, 1956; Mond, 1863).

During this time Mond became very friend with John Tomlinson Brunner (1842-1919), a friendship, which would continue all their lives and would result in the building of a chemical empire. Brunner was chief clerk to Hutchinson & Co. but like Mond had a strong desire to be his own master. Brunner, although not technically educated, seemed to understand Mond's ideas and to help him concentrate his mind in one thing a time (Roberts, 1869).

After his marriage in 1866, Ludwig and his wife moved to Farnworth, about three miles northwest of Widnes.

The Mond process was not particularly successful in England, where sulfuric acid was cheap anyway, but it was used in several plants and eventually yielded Mond reasonable royalties. It was seen of sufficient scientific interest at the time for Mond to give a lecture, *On the Manufacture of Sulfur from Alkali Waste in Great Britain*, to the British Association at Norwich in August 1868 (Abel, 1869).

Mond visited with Ernest Solvay (1838-1922) in 1872 and obtained from him a license for the ammonia soda process. Upon his return to England he formed a partnership with Brunner for its exploitation and together they put up a factory in Winnington Hall. The site was selected because it was near to the port of Liverpool, to a railway, and to coal and limestone sources. By 1881 the business was flourishing. Mond and Brunner retained the controlling interest in what was by then the largest alkali works in the world, becoming immensely wealthy in the process (Roberts, 1869).

In 1889 Mond and his family moved to London where they bought a very large house in Winnington and built there a well-equipped laboratory where Mond centred his research and development. An indication of the activity may be gained by the 40 patents registered over the years from this laboratory (Roberts, 1869).

One of processes coming out from Winnington was the preparation of nickel carbonyl. Mond realized immediately the possible use for this carbonyl as the key of a process for the purification of nickel from its ores. He went on to build a pilot plant at Wiggin Nickel Works at Smethwick and soon he was producing sizeable quantities of the purest nickel. The Swansea factory is still producing nickel of the highest purity via nickel tetracarbonyl (Roberts, 1869).

Mond believed that the study of pure science is the best

preparation for a career in industry. He used his great wealth wisely; particularly notable gifts were the Davy-Faraday Laboratory at the Royal Institution and financial support to the Royal Society for the publishing of the Catalogue of Scientific Papers. In honour of Stanislaio Cannizzaro (1826-1910) he founded at the Dei Lincei Royal Academy the conspicuous prize named after him, which was delivered for the first time in 1911. Mond was a great admirer of the early Italian painters, and he collected at his London house one the finest galleries of their works in England. At his death he bequeathed them to the nation (Watts, 1918).

In 1881 Mond was appointed one of the four honorary secretaries of the newly formed Society of Chemical Industry, which begun as a club in Widnes and then expanded into a nation-wide organization, intended to give industry some sort of corporate activity (Cohen, 1956).

On December 6, 1902, he had a heart attack, from which he got up as an invalid and as such remained for the remaining seven years of his life.

Mond died at this home on December 11, 1909, and was buried on the Saint Pancras Cemetery, East Finchley. He had suffered from a weak heart for many years (Watts, 1918). He was survived by his wife and three children: Robert Ludwig (1867-1938), Alfred Moritz (1868-1938), and Edith (1970-1905).

Alfred Mond became responsible of running his father's industrial empire, becoming chairman of the Mond Nickel and a founder of ICI (Imperial Chemical Industries). He was also a major political figure as Member of Parliament, becoming a cabinet minister of health in the Lord George (David Lloyd George, 1863-1945) administration of 1921. He became 1st Baron Melchett in 1928 (Abel, 1989).

Honours and awards

Mond received many honours for his contributions to science and industry. He was instrumental in founding the Society of Chemical Industry and was elected its first president in 1881, and was again president in 1889. He was awarded Doctor of Science degrees (*honoris causa*) by the University of Padua (1892), the University of Heidelberg (1896), and the University of Manchester (1904); as well as a LL. D. degree (*honoris causa*) by the University of Oxford (1907). He was elected fellow of the Royal Society (1891), honorary member of the German Chemical Society (1908), honorary foreign member of the Royal Society in Naples (1908), and foreign member of the Prussian Academy of Science (1909). In 1908 the Italian King awarded him the Grand Cordon of the Crown of Italy (1908).

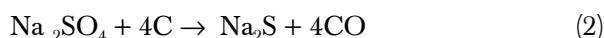
He was active in Manchester, as governor of Owens College and later as member of the University Court.

Scientific and industrial contributions

The Catalogue of Scientific papers, published by the Royal Society of London (Royal Society, 1921), lists 17 papers written by Mond, alone or with colleagues.

1. Ammonia soda process

Around 1870 the Leblanc process was the prevailing process for the manufacture of sodium carbonate. It consisted of a first step for producing sodium sulfate by the reaction between sodium chloride and sulfuric acid. Afterwards, the sulfate was reduced with coal to the sulfide, which in turn was reacted with chalk or lime to form soda and calcium sulfide, yielding what was called black ash (Wisniak, 2003).



The main components of black ash were approximately 41.6% weight sodium carbonate, 29.8% calcium sulfide, 11.6% calcium carbonate, and 4.4% coke.

After the peace of 1802, William S. Losh, of Walker-on Tyne, England, visited France, learned the details of the Leblanc process and in 1814 used the process to make small quantities of soda in England. James Muspratt (1793-1886) who was making prussiate of potash, acids, and solvents in Dublin and afterwards in Liverpool, hired in 1828 J. C. Gamble (1776-1848), a Glasgow-trained chemist, and began making soda on a large-scale plant in Liverpool. In 1825, Charles Tennant (1768-1838), a manufacturer of bleaching powder, initiated the manufacture of Leblanc alkali at Glasgow (Wisniak, 2003).

Initially, expansion of the industry in Britain was greatly hindered by the high revenue tax of thirty pounds charged on every ton of common salt used (Salt Act). Abolition of this tax thirty years later, led England to be the world leader in soda production, the industry grew steadily and by the middle of the eighteenth century it occupied a strategic position in the economy. In 1862 it consumed nearly two million tons of raw materials, produced about 280,000 tons of finished product and occupied about 19,000 people directly or indirectly (Wisniak, 2003).

Leblanc's process remained viable during 80 years until the advent of Solvay's process in 1863. During this period it went through many improvements but its basic chemistry remained the same: common salt, sulfuric acid, charcoal, and limestone were used to produce cheap sodium carbonate. The process required large amounts of material; in order to produce one ton of carbonate six tons of raw material were required and produced thirteen tons of solid, liquid, and gaseous refuse, all of which had to be disposed of in some

way. Two of the by-products were particularly harmful and contaminating: one gaseous (hydrogen chloride) and one solid (calcium sulfide). Production of one ton of sodium carbonate generated about 0.75 tons of HCl and two tons of sulfide (Wisniak, 2003).

Other important disadvantages of the process were related to waste of valuable chemicals: sulfur from the sulfuric acid was confined in the calcium sulfide and lost along the unreacted coal and limestone. The initial implementation of Leblanc's process was also accompanied by the loss of most of the hydrogen chloride. The problem of disposal of hydrogen chloride was eventually solved in 1836 by William Gossage's (1799-1877) invention of absorption towers in which the gas was absorbed in a stream of water flowing counter-current to the gas (this was the first practical absorption tower). By using coke or other porous material the device was subsequently improved to the point where emissions of gas could be virtually eliminated. It took more than sixty years and stringent environmental laws to increase the recovery to almost one hundred percent (Wisniak, 2003).

By the time that Ludwig started his apprenticeship at Ringenkühl, part of the acid was now condensed in water and run to waste. At a later date chlorine was recovered from it, and a quarter of the wasted hydrogen chloride was used for the manufacture of bleaching powder.

The measures taken by the manufacturers to solve the problem of obnoxious gases turned to their benefit. Gaseous hydrogen chloride was transformed into a liquid solution that not only could be used as such it also became a source of chlorine, which was extensively required for the textile, paper, water treatment, and other industries as bleaching powder. Way before chemists were aware that hydrogen chloride could be reacted with oxygen and transformed into chlorine. Between 1869 and 1870 Walter Weldon (1832-1885) implemented the oxidation of HCl using manganese dioxide. Weldon's process transformed manganese oxide into manganese chloride, from which the dioxide could not easily be regenerated (Wisniak, 2003).

The waste of solid residue of calcium sulfide was used to fill in ditches and marshes and construct railroad embankments, but eventually it was heaped wherever spare land could be found and increasingly came to dominate the landscape. Rain gave place to hydrogen sulfide release giving very unpleasant smells. In the summer months, the solid residues released large amounts of hydrogen sulfide, with the corresponding noxious effect in the neighbouring areas. In addition, during the rainy season, the water wash of these residues generated large amounts of a yellow liquid that contained sulfur and calcium polysulfide that leaked into the water sources and contaminated them. Dumping of the solid residue meant not only an ecological problem but also the

loss of all the sulfur used in the Leblanc process. This was a serious economical drawback since sulfur was an expensive raw material, imported mainly from Sicily, and essential for the fabrication of sulfuric acid. In order to break the Sicilian monopole, the British started about 1839 to manufacture sulfuric acid using pyrites imported from Spain. It was obvious then that ways had to be found to recover the sulfur contained in the solid residue of Leblanc's process (Wisniak, 2003).

In a paper published in 1865, Mond indicated that in 1864 the amount of salt decomposed in England amounted to 288,000 tons and that its transformation into sodium sulfate required about 320,000 tons of sulfuric acid, which contained about 100,000 tons of sulfur (Mond, 1865). The wet waste, known variously as alkali waste, blue waste, or tank waste, contained no more than 12 percent sulfur.

As mentioned before, Mond entered the works of John Hutchinson and Co. at Widnes in order to demonstrate the viability of his sulfur recovery process, and if possible to sell his patent. He soon found that it was not entirely adapted for large-scale manufacture where the cost of operation was an important consideration, and he patented an improvement on September 8, 1863. This consisted in carrying out the oxidation in the black ash lixiviating vats by blowing air through the waste and repeating the operation after one or two washings with water. Subsequently, Mond introduced the use of wastewater from the chlorine stills in place of fresh hydrogen chloride for the decomposition of the soluble sulfur compounds, with the separation of free sulfur (Watts, 1918).

By 1870-1871 Bruner and Mond decided to leave Hutchinson and put up a Leblanc factory, a sulfur recovery plant to take in waste and sell sulfur, and other enterprises.

Many unsuccessful attempts had been made to develop a simple alternative to the Leblanc process by treating salt solutions with ammonia and carbon dioxide. By 1856 Solvay (Solvay, 1863) had brought the process to some measure of efficiency, and the meeting between Mond and Solvay led to Mond's acquisition in 1872 of a license to use the process in England. According to Roberts (Roberts, 1989) calculations by Mond and Brunner of the relative cost of manufacture of soda ash by the Leblanc and Solvay processes indicated a cost production of £7.8s.3p. for the production of one ton of soda ash by the Solvay against £9.7s.6p. for the Leblanc process. The key advantages lay on the cost of salt brine solution for the ammonia soda for Leblanc, fuel usage, and wages. Mond and Brunner put up the Solvay plant in Winnington. Despite the assistance and design of Solvay, the differing raw materials, engineering problems and inexperienced workers, the plant went from crisis to crisis. During year 1874 they produced 838 ton at a loss of £4300, which

was about 25% of the capital sum invested. By 1875 2048 ton had been manufactured at a profit of £2405. Mond made significant improvements in the recovery of ammonia and larger scale industrial operation and transformed the corporation of Brunner and Mond into the first real threat to the survival of the Leblanc soda trade (Mond, 1885, 1890).

The source for a cheap source of ammonia for his soda works led Mond to examine ways of obtaining ammonia from coal, which at that time was being purchased and transported from the Liverpool gasworks. He tested several alternatives, using bones and waste leather, distillation from coal, or using the nitrogen of air. The latter was based in reacting barium carbonate with carbon and nitrogen to give barium cyanide. The barium cyanide was then allowed to react with steam to give ammonia and barium carbonate



This alternative was eventually discarded because the problems with the materials of construction and the need to heat to over 1400°C.

After much experimentation Mond selected a procedure based on burning coal in gas producers using a mixture of air and steam (Mond, 1885). The key to Mond's plant was the design of an improved furnace and a better utilization of the waste heat generated. It included vaporization of the water and preheating of the air before entering the furnace. His findings indicated that the yield of ammonia varied inversely with the operating temperature of the producer, and that the temperature could be controlled by regulating the amount of steam admitted with the blast; the lower the temperature, the higher was the yield of ammonia. The best results were obtained by using about two tons of steam for every ton of fuel gasified. He succeeded in converting one-half of the nitrogen existing in the fuel into ammonia, getting about 8 kg of ammonia per ton gasified. In addition to ammonia the system yielded a cheap gas suitable for most heating processes; it contained, in the dry state, about 15% of CO₂, 10% of CO, 23% of H₂, 3% of ethylene, and 49% of nitrogen (now known as Mond gas), with a caloric value about 73% of the caloric value of the fuel used. In using this gas for heating purposes, such as generating steam or making salt, the heat released was utilized more efficiently than in burning fuel, since it completely burned with almost the theoretical quantity of air, so that the combustion products contained less than 1 to 2% of free oxygen (Mond, 1889).

Mond gas was soon used for heating furnaces and operating gas engines, and proved so satisfactory that a large plant was installed at Winnington. To promote its local use, the South Staffordshire Mond Gas Company was formed, and to develop the process overseas Mond founded the South Staffordshire Power Gas Corporation at Tipton, near

Dudley Port. Here fuel was gasified in Mond producers and, after purification, it was compressed and delivered into mains that conveyed it to consumers in about 160 works. By the early 1900s, Mond's Dudley Port Plant in Staffordshire was using 3 million tons of coal each year to make producer gas (Watts, 1918).

In his 1889 Presidential address to the Chemical Society Industry Mond described the enormous potential of this discovery, in these words: "The introduction of coal gas for illumination gave us a considerable and constantly increasing supply of ammonia as a by-product of the gas manufacture and until recently all practical efforts to increase our supply of ammonia were directed towards collecting and increasing in the best possible manner the ammonia so obtained. The immense extension of the coal gas industry all over the world has in this way put us into possession of a very considerable amount of ammonia sulfate, amounting in Europe now to 140,000 ton per year. In recent years this has been augmented by the ammonia obtained by the distillation of shale, by the introduction of closed ovens for the manufacture of coke, combined with apparatus for condensing the ammonia formed in this manufacture, and also by the condensation of the ammonia contained in the gases from blast furnaces working with coal. But all these new sources have so far added only about 40,000 ton of ammonia sulfate to our supply, making a total of 180,000 ton per year. Of this about 120,000 ton are produced in England, while we still import 650,000 ton of sodium nitrate from Chile, equivalent to 500,000 ton of ammonia sulfate, to make up our requirement. The enormous consumption of fuel in England, amounting to not less than 150 million ton/year, would at this rate yield as much as 5 million ton of ammonia sulfate per year, that if only one-tenth of this fuel would be treated by the process, England alone could supply the whole of the nitrogen compounds, ammonia sulfate, and sodium nitrate at present consumed by the Old World" (Mond, 1889).

Chlorine

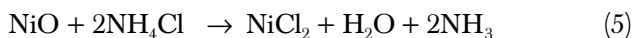
By 1886 the ammonia soda process had developed to such an extent that it had become a serious competitor to the Leblanc process; but as such it possessed one defect: it wasted all the chlorine of the sodium chloride, and so produced no bleaching powder. Mond's calculations showed clearly that the ammonia process was much cheaper than the Leblanc process and from this he inferred that the day would come when the Leblanc would become a process for the manufacture of bleaching powder and that sodium carbonate would be a by-product of it, of which it would have to dispose of at any price it could obtain. He therefore undertook a series of experiments with the object of producing bleaching powder as a by-product of the ammonia soda process (Mond, 1895).

By 1882 he had already patented a process for making calcium peroxide to be used as a substitute for bleaching powder. He followed this in 1883 by a process for obtaining hydrogen chloride.

As mentioned before, the ammonia soda process produces as a by-product a solution of calcium chloride. Some investigators had tried to produce chlorine from the calcium chloride obtained by evaporating these solutions; others had proposed to substitute magnesia for the lime in distilling the solution of ammonium chloride and to produce chlorine or hydrogen chloride from the magnesium chloride obtained by evaporating its solution. Thus, for example, the process proposed originally by Weldon to recover the chlorine began by treating the residual liquor with ground chalk or limestone to neutralize the free acid and precipitate any sulfuric acid and iron oxide present. The clarified liquor was then treated with milk of lime to precipitate the manganese in the form of protoxide. More milk of lime was then introduced and air blown in to convert the manganese into peroxide. After clarification the mud (Weldon mud) was reacted with hydrogen chloride, chlorine was released and the residual liquor treated as before. In 1872 Weldon suggested a modification to produce hydrogen chloride instead of chlorine: lime was replaced by magnesia yielding magnesium chloride instead of calcium chloride. Hydrogen chloride was then produced from magnesium chloride by a process patented by Clemm in 1860, viz., by evaporating the solution, heating the residue in the presence of steam and condensing the acid vapours given off (Mond, 1896a).

The above ideas were adapted by Mond to produce hydrogen chloride and chlorine directly from the residual liquids of the ammonia soda process. In these liquids the chlorine remains in solution in combination with ammonia, along with residual sodium chloride. Mond separated the two salts by partial evaporation to crystallise the sodium chloride, followed by drying to obtain solid ammonium chloride. He found that nearly all metallic oxides, with the exception of the alkalis and alkaline earths, and even a large number of metallic salts, decomposed the ammonium chloride vapours forming a metallic chloride and releasing ammonia. The metallic chlorides gave up their chlorine and reconverted into oxides by the action of air at a suitable temperature. The best results were obtained with nickel oxide and the next best with magnesia mixed with a certain amount of potassium chloride (Mond, 1886a,b; 1896a,b).

In Mond's process, patented in 1886 (Mond, 1886a), the dried ammonium chloride is volatilized by heat and the vapours passed over nickel oxide or other metal oxide at about 400°C. Nickel chloride is produced and the free ammonia is blown out to be absorbed in water and eventual return to the soda process:

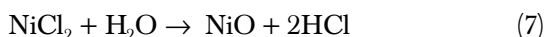


Dry air is then blown through the nickel chloride at 500°C and chlorine gas is released according to (Mond, 1896a):



The chlorine is then utilized in a Deacon chamber for producing bleaching powder.

Substitution of air by steam leads instead to the formation of hydrogen chloride (Mond 1886a):



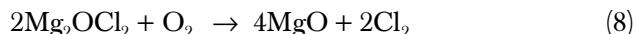
The process for the manufacture of ammonium chloride was superseded by a cold one wherein the liquors were cooled by freezing machines until the ammonium salt separated. This was found to yield a product of great purity, an essential property for a salt, which had to be volatilized.

In order to secure the exposure of a large surface to the action of the gases Mond made up the nickel oxide into pills by mixing it with china clay and pressing it between rollers with hemispherical cavities. Mond found that after these pills had been used for some weeks, they became black, swelled up, and disintegrated into powder. Investigation showed that, in this condition, they contained a considerable amount of carbon originating from the carbon monoxide present in the gas used to sweep out the last trace of ammonia from the apparatus before proceeding to evolve chlorine. A study of the behavior of these gases in the presence of nickel oxide and their action on metallic nickel led Mond and Langer not only to devise a method for removing carbon monoxide from producer gas, but also to the discovery of nickel carbonyl (see below).

The many problems caused by the disintegration of the nickel oxide pills forced Mond to return to the use of magnesia in which magnesium oxychloride was produced instead of nickel chloride, and the oxychloride was decomposed by heating in dry air at 800°C.

At 300°C a reaction similar to reaction 5 above takes place, where the ammonium chloride is decomposed by the magnesia with the formation of magnesium chloride and ammonia. It was found that this magnesium chloride retained part of the steam formed by the reaction and this humidity led to the formation of a considerable amount of hydrogen chloride during the treatment with hot air. Mond succeeded in reducing the amount of hydrogen chloride to a negligible amount by adding to the magnesia a certain amount of potassium chloride, which probably had the effect of forming an anhydrous double chloride. The mixture of magnesium and potassium chloride was made into pills by the same procedure used for nickel oxide (Mond, 1896b).

The mixture was now heated to 600°C in a current of hot dry gas, containing no free oxygen (the gas from the carbonating plant being used) and then a current of air at the same temperature passed in. Decomposition took place according to



Initially the resulting gas contained between 18 and 20% of chlorine; this percentage dropped gradually and when it reached about 3% the apparatus was cooled down to about 350°C, by the admission of air. The air stream containing the small percentage of chlorine was led off to a second cylinder of pills, which had just been treated with ammonium chloride vapour and were ready for the hot air current (Mond, 1896a).

In his talks to the Chemical Section of the Society of Chemical Industry (Mond, 1896a,b) Mond pointed out that other methods were being pushed forward in the world to produce chlorine, particularly electrolysis. According to Mond, these methods had still, to stand the test of time before a final opinion could be arrived at as to the effect they would have upon the manufacture of chlorine... "I do not believe that chemical industry will in future be diverted from this section (Chemistry) and have to wander to Section A under the ægis of applied electricity. I do not believe that the easiest way of effecting chemical changes will ultimately be found in transforming heat and chemical affinity into electricity, tearing up chemical compounds by this powerful medium, and then recombine their constituents in such form as we may require them. I am sure that there is plenty of scope for the manufacturing chemist to solve the problems before him by purely chemical means, of some of which we may as little dream today as a few years ago it could have been imagined that nickel would be extracted from its ores by means of carbon dioxide."

With the coming of large-scale electrical power generation in the 1890's, the chloro-alkali industry was born. From this point on, the Leblanc-Deacon process became a major producer of chlorine used as bleach in the paper and textile industries.

As mentioned by Roberts (Roberts, 1989) Mond's failure over the 1890-1909 period was undoubtedly his lack of belief in the future of the electrolytic production of caustic soda and chlorine, in spite of the experience that his firm had acquired in electrolysis. It was to be twenty years later, and after Mond's death, that Brunner-Mond finally, and too much greater expense, bought their way into electrolysis (Roberts, 1989).

Fuel Cells

In 1800 William Nicholson (1753-1815) and Anthony Carlisle (1768-1840) described the process of using electricity to decompose water into hydrogen and oxygen and in 1838 William Robert Grove (1811-1896) discovered that by ar-

ranging two platinum electrodes with one end of each immersed in a container of sulfuric acid and the other ends separately sealed in containers of oxygen and hydrogen, a constant current would flow between the electrodes (Grove, 1839). The sealed containers held water as well as the gases, and Grove noted that the water level rose in both tubes as the current flowed. The "Grove cell," as it came to be called, used a platinum electrode immersed in nitric acid and a zinc electrode in zinc sulfate to generate about 12 amps of current at about 1.8 volts. Combining the gases to produce electricity and water was, according to Grove, "a step further than any hitherto recorded." Grove understood that combining several sets of these electrodes in a series circuit might "effect the decomposition of water by means of its composition." He soon accomplished this feat with the device he named a "gas battery"—the first fuel cell. A fuel cell is an electrochemical device that converts the chemical energy of a fuel directly into direct current electricity, in a continuous manner. In contrast with a battery, it can supply electrical energy over a long period of time because the cell is fed continuously with fuel and air from an external source.

Fuel cells remained a curiosity for many years until Mond and Langer pushed the idea a long step forward by considering the possibility of building a dry battery in which the producer gas took the place of hydrogen. As they had done in many opportunities before, their first step was to become familiar with the phenomenon. For this purpose they constructed a Grove cell, operated it with pure hydrogen and learned its characteristics. Very soon they realized that the cell operated very slowly and that there were many operational difficulties in using liquid electrolytes. They found that platinum black lost its adsorbing power almost completely as soon as it got wet and that, therefore, it was necessary to keep it comparatively dry. All attempts to attain this with various constructions of the gas battery involving the use of a liquid electrode failed. This led to the need to find better electrodes, which he described in one of his presidential addresses (Mond, 1888a). After a long series of experiments Mond and Langer developed a new cell in which the strips of aluminium foil as used by Grove, partly immersed in dilute sulfuric acid, were replaced by a number of elements formed of a porous diaphragm of a non-conducting material, such as plaster of Paris, earthenware, asbestos, and pasteboard, impregnated with dilute sulfuric acid. The diaphragms were covered on each side with very fine platinum leaf perforated with numerous small holes and covered with a thin film of platinum black. The coatings were in contact with frameworks or lead and antimony, insulated one from the other, which conducted the electricity to the poles of the battery. A number of these elements were placed side by side, with non-conducting frames intervening so as to

form chambers through which the hydrogen gas was passed along one side of the element and air along the other. Thus, the cell became practically a dry battery. In their own words: "We have only succeeded by using an electrolyte in a quasi-solid form, viz., soaked up by a porous non-conducting material, in a similar way as has been done in the so-called dry piles and batteries" (Mond, 1889, 1888a).

The electromotive force of the battery was found to vary considerably according to the way in which platinum black was prepared. The best results were obtained from platinum black made by neutralizing a boiling solution of platinum tetrachloride with sodium carbonate and adding this slowly to a boiling solution of sodium formiate.

According to Mond, this peculiar construction allowed them to get a very large amount of duty from a very small amount of platinum. For example, a battery consisting of seven elements with a total effective surface of 0.5 m², containing 2.5 g of platinum leaf and 7 g of platinum black produced a current of 2 amp and 5 volt, or 10 watt. This current was equal to nearly 50% of the total energy obtainable from the hydrogen adsorbed in the battery. The water produced in the battery by the oxidation of hydrogen was carried off by the inert gas mixed with hydrogen and by the excess air. This was important because if platinum black becomes wet it loses its adsorbing power for the gases almost completely and stops the operation of the battery.

The next step was to study the performance of the battery using producer gas instead of pure hydrogen. The results were very satisfying: it made no difference to use pure oxygen and hydrogen or air and gases containing 25% of hydrogen. The only difficulty was that the carbon monoxide and hydrocarbons present in the gas destroyed the adsorptive power of the platinum black coated electrode. In search of a cheap method of removing these impurities they discovered that if a mixture of steam and gas was passed at temperatures between 350° to 450°C over finely divided nickel or cobalt, the carbon monoxide was converted into carbon dioxide and carbon, the hydrocarbons split into carbon and hydrogen, and the resulting gas contained 36 to 40% hydrogen (Mond, 1888b). The finally divided metals were prepared by impregnating pumice stone with salts of these metals, followed by reduction by means of hydrogen or producer gas. The producer gas thus purified and enriched in hydrogen yielded good results with the battery; but unfortunately, the life of the battery itself was not long enough, it showed polarization after it had been working for some time. This resulted in a loss of electromotive force of 4 to 10 percent within an hour. Additional experimentation showed this to be caused by transport of the sulfuric acid from the oxygen to the hydrogen electrode. The problem was partially solved by exchanging the gases in the battery from time to time, so

that the current went in an opposite way through the porous diaphragm and transported the sulfuric acid back (Watts, 1918).

It was subsequently found by others that a carbon base permitted the use of much less platinum. Friedrich Wilhelm Ostwald (1853-1932, 1909 Nobel Prize for Chemistry) proposed as a substitute for the heat engine generators, electrochemical cells in which carbon would be oxidized to CO₂ by oxygen,

According to Mond's calculations (considering the steam engines which were then available) if the same amount of hydrogen adsorbed in the battery was burned in a steam boiler, the steam generated converted into mechanical motion and then into electricity, the yield of electricity would in the most favourable case not exceed 8% of the energy in the gas. Mond expressed his hope that one day this kind of battery would enable to perform chemical operations by electricity on the largest scale, and press this potent power into the service of the chemical industries (Mond, 1889).

Mond's results on the adsorption of hydrogen and oxygen by platinum led to some common research works with William Ramsay (1852-1916) and John Shields on the occlusion of oxygen and hydrogen by platinum and palladium (Mond et al., 1897a,b).

Nickel tetracarbonyl

The development of a process for the production of cheap chlorine by the decomposition ammonium chloride vapours confronted Mond and Langer with a very serious problem in finding the appropriate construction materials, and in doing so to come across a new chemical reaction. When doing pilot plant work they found that the vapours of ammonium chloride not only attacked metal oxides, which were the basis of the process, but also it violently corroded the large majority of metals. This problem was solved by lining the reaction vessels with glazed tiles and using nickel as the construction material for the valves for changing from the current of ammonium chloride to hot air, and vice versa, which had to be very tight to prevent a large loss of ammonia. On the laboratory scale these nickel valves worked perfectly, but when applied on a manufacturing scale they soon became leaky. Examination of the valves showed that they had become covered with a black crust, containing carbon. This was the same phenomenon observed with the pellets of nickel oxide and china clay employed in the decomposition of ammonium chloride (Mond, 1895).

A detailed analysis of both processes suggested to Mond and Langer that the reason of the failure was connected with the gas used to sweep the ammonia from the reactor. In the laboratory this was pure nitrogen but in the plant they used the residual gas evolving from the Solvay tower, which

scrubbed the residual ammonia. This gas contained nitrogen and a few percent of carbon monoxide. It was clear then that the carbon originated from this carbon monoxide.

Mond and Langer decided then to study the reaction of NiO with CO. Preliminary experiments with carbon monoxide showed that nickel oxide promoted the reaction



and this explained the black deposit observed on the pellets.

The next series of experiments was the study of the reaction of CO with pure nickel. In these, finely divided nickel was treated with pure carbon monoxide in a glass tube at varying temperatures for a number of days and then cooled in a current of carbon monoxide before it was removed from the tube. In order to keep the poisonous carbon monoxide out of the atmosphere of the laboratory, the exiting gas was connected to a Bunsen burner and lighted. These tests were initiated every day and terminated in the evening, and then the nickel allowed cooling down. In one of these opportunities Langer observed that as the apparatus cooled to about 150°C the flame of the burner became luminous and increased in brightness until the temperature fell below 100°C while its colour changed from its normal blue to greenish yellow. Initially these observations were assumed to be the result of impurities in the materials; e.g., the sulfuric acid perhaps contained some arsenic, which was burning in the form of arsenic trihydride. When Langer heated the glass tube through which the gas passed to the burner, a bright, not a dull, metallic mirror was formed and the Bunsen flame lost its luminosity. In addition, the flame gave a mirror on a cold porcelain plate. This deposit was found to be not arsenic but pure nickel. Further experiments showed that the metal of the mirror had an atomic weight of 58.58, which corresponded very closely to that of nickel. These observations explained the disintegration of the nickel valves and pills during the manufacture of chlorine.

Instead of burning the gas, it was now first bubbled through cuprous chloride to eliminate the excess of CO and then heated to 180°C in aniline vapour to decompose the remaining fraction. It was found that a very small quantity of nickel resulted in the release of a large quantity of CO, which converted into a very voluminous black mass containing varying quantities of carbon up to 85%. When hot this mass was pyrogenic so that to analyse it was necessary to cool it in a current of pure CO.

It was thus evident that a volatile compound of nickel and CO had been obtained, which on heating to 150°C completely dissociated into its constituents. The increase in volume proved that one volume of gas yielded four volumes of CO, and the determination of the amount of nickel deposited and the CO formed led to the proportion of four

equivalents of CO to one of nickel, that is, the compound formed was $\text{Ni}(\text{CO})_4$ (Mond, 1891).

The volatile compound had a density of 6.01 at 50°C. It was liquefied with a refrigerating mixture of snow and salt and shown to be a colourless, mobile, highly refracting liquid, having a specific gravity of 1.3185 at 17°C, and possessing a characteristic odour. It was soluble in a large number of organic liquids, such as alcohol, ether, chloroform, benzene, petroleum, tar oils, etc. It boiled at 43°C and 751 mmHg without decomposition, evaporated rapidly at ordinary temperature in a current of other gases, and solidified at -25°C forming needle-shaped crystals. The vapour exploded when suddenly heated to above 60°C and also when the tube containing it was scratched roughly with a knife. A mixture of the vapour with air exploded violently on the application of flame. Both the liquid and the vapour were poisonous, the latter approximating CO in this respect. Experiments with rabbits showed that a sub-cutaneous injection of a very small dose of a solution of the liquid in chloroform led to an extraordinary reduction in temperature, amounting in some cases to 12°C.

Nickel tetracarbonyl was found to be, in general, chemically very inactive. It did not react with alkalis and acids (excepting nitric acid and aqua regia). It only reacted with substances having a considerable affinity for nickel, such as the halogens, sulfur, oxygen, and oxidizing substances. These combined with the nickel and liberated CO. Chlorine and bromine when used in excess also entered into combination with the CO. Sulfur in the dry state formed a nickel sulfide corresponding the formula Ni_2S_3 , which dissolved in CS_2 forming a sulfide containing more sulfur, but of varying composition (Watts, 1918; Mond et al., 1890; Mond, 1891).

The discovery of nickel carbonyl was reported to the Chemical Society in a paper read before its members on June 19, 1890 and published in the Society journal. The nature and properties of nickel carbonyl were so novel that they initiated an international race to find the carbonyls of other metals. Initially the carbonyl reaction was tried with many metals and, except for iron, it failed.

The next member of the family, iron pentacarbonyl, was reported virtually simultaneously by Mond (Mond and Quincke, 1891; Mond, 1908) and by Marcellin Berthelot (1827-1907) (Berthelot, 1891). Iron metal was prepared by reduction of the oxalate in a current of hydrogen and then treated with carbon monoxide at about 80°C. The resulting gas imparted a yellow tinge to a Bunsen flame and yielded slight metallic mirror composed of pure iron. It liquefied into an amber coloured liquid, which on standing deposited tabular crystals of a darker colour, and solidified entirely below -21°C to a mass of needle-shaped crystals. It boiled at 102°C leaving a small quantity of green-coloured oil behind

(Mond, 1891). Mond succeeded in preparing iron carbonyl, but found that at ordinary pressure no results were obtained with any of the large number of metals, which he employed. At high temperature and under extreme pressure, however, he succeeded later in obtaining carbonyl of cobalt at 100 atm and 200°C (Mond, 1908), of molybdenum at 250 atm and 200°C, and of ruthenium at 450 atm and 300°C. The carbonyls were characterised by similar properties: (a) when heated they decompose into carbon monoxide and the metal which is deposited in the form of a bright metallic mirror; (b) they are not attacked by non-oxidising acids but are quickly dissolved by oxidising acids, and especially by aqueous solutions of the halogens, with evolution of carbon monoxide; (c) at least one of the carbonyls of each metal is volatile without decomposition, and can be purified by distillation or sublimation; (d) they are all more or less soluble in the usual organic solvents, such as ether, ethanol, benzene and oils and, (e) they are all insoluble in water. The physical properties were found to vary considerably, from nickel tetracarbonyl, a very volatile liquid with a specific gravity of 1.32, to the non-volatile $\text{Fe}_2(\text{CO})_9$, with a specific gravity of 2.085. The colour varied from colourless for liquid $\text{Ni}(\text{CO})_4$ to rose to orange, for crystals for ruthenium. Some can be obtained in the form of gas, liquid, or solid, and others still only in the solid state. The account of this work, carried with the assistance of Hirtz and Cowap, formed the substance of the last publication under Mond's name. One of the papers carries a detailed table of the properties of carbonyls prepared (Mond, 1910a,b).

Nowadays, a very large number of metal carbonyls have been synthesized and gave place to a series of industrial processes, such as the water shift reaction, the Monsanto acetic acid process, hydroformylation reactions, and Reppe carbonylations (Abel, 1989).

Manufacture of nickel

Nickel occurs in nature along with varying quantities of copper and iron and is also found in metallurgical products such as nickel speiss (an arsenic compound or a mixture of arsenic compounds resulting from the smelting of iron, cobalt, nickel, and copper ores) and nickel matte (an artificial nickel iron sulfide, produced by smelting, containing between 25 to 45% nickel). The carbonyl experiments had shown Mond that copper does not form carbonyls and that the CO-forming impurities in crude nickel ore did not volatilise: $\text{Fe}(\text{CO})_5$, with a boiling point of 103°C has a very slow rate of formation; cobalt forms $\text{Co}_2(\text{CO})_8$, melting at 51°C and decomposing at 52°C to form $\text{Co}_4(\text{CO})_{12}$, but both carbonyls are solid with very low volatility. Mond realized that he had here a potentially unique method of making pure nickel, a metal, which was just beginning to have importance

in metallurgy. An alternative process was the Orford process, which relied on the much greater solubility of Cu_2S in Na_2S than nickel sulfide (Roberts, 1989).

These facts led Mond to carry out experiments to ascertain whether it would be possible to use CO to extract nickel directly from its ores and from nickel speiss and nickel matte, and then deposit it in a very pure state: The nickel would volatilise at ordinary temperature in the form of a vapour mixed with other gases, and would then be deposited as a metal in the form of bright coherent masses of great purity by simply heating the gases to a moderate temperature of 200°C . The CO liberated would be recycled.

Experiments carried out with a great variety of ores from all parts of the world, containing from 4 to 40% nickel, as well as a number of samples of nickel speiss and nickel matte, proved that as long as the nickel was combined with arsenic or sulfur the process was entirely successful. It was only necessary to calcine the raw material to convert the nickel completely into oxide, and then reduce it with hydrogen gases, in practice water gas, at 450°C . The reduced mineral was then cooled down to room temperature and treated counter-current with CO. The gas loaded with the nickel carbonyl was then passed through tubes or chambers and heated to about 200°C , resulting in precipitation of almost chemically pure nickel (Mond, 1895; 1891).

In 1892 an experimental plant was built on Henry Wiggin's factory at Smethwick near Birmingham. Very soon it was producing nickel at the rate of 1.5 ton per week from the Canadian nickel copper matte imported into England. This matte, which contained about 40% of nickel and an equal quantity of copper, was carefully roasted to drive out the sulfur as far as possible, and was then reduced with water gas or producer gas, rich in hydrogen, at a temperature not exceeding 400°C . The resulting mass, now reduced to the metallic state, was taken in airtight conveyers and elevators to another apparatus where it was treated with CO at a temperature not exceeding 80°C . The CO gas, loaded with nickel carbonyl, was then passed through a series of chambers, heated to about 180°C , where the nickel deposited in various forms, according to the speed of the gas current, the richness of the gas, and the existing temperature. The liberated CO was then recycled (Mond, 1895).

To increase production Mond needed a source of ore and a suitable site for the plant and for this purpose he purchased two ore bodies near Sudbury in Ontario, Canada. The major center of metallurgical industry in England was in South Wales and it was there that Mond built his plant and established, in 1900, the Mond Nickel Company (Mond, 1895; 1908).

In 1899 William Chandler Roberts-Austen (1843-1902) gave a very detailed description of the nickel works located at Smethwick, near Birmingham (Roberts-Austen, 1899).

Mond went forward and looked into possible additional uses for nickel. He found that if the metal was allowed to deposit slowly at a carefully regulated temperature, it could be easily obtained from the gas as a coherent metallic film, so that it was possible to coat any substance which can stand heating to 1500°C , with a perfect covering of metallic nickel, and also make articles of metallic nickel for direct use. He believed that the great facility with which hollow nickel goods could be made in this way, which at that time could not be made at all, or only by the use of very powerful hydraulic machinery, would give great impetus to the manufacture of nickel utensils for domestic purposes, the use of which was so very desirable from a sanitary point of view (Mond, 1895).

White lead

Through Professor Gustave Bischoff, professor of chemistry at the University of Bonn, Mond became interested in the manufacture of white lead. The traditional process for making this basic carbonate came from Holland and was very complicated and costly because of the operational capital needed. The reaction vessels were earthenware pots, with a false bottom in the lower third. This bottom was filled with vinegar, while the top two thirds were filled with strips of lead sheeting. A layer of these pots were placed on the floor of a shed and surrounded up to the rims with fresh dung or spent tan bark, and urine. The shed was left to heat up by fermentation of the dung and to react for two to three months. The heating evaporated the vinegar and the acetic acid attacked the lead to form various acetates. The carbon dioxide from the decomposition of the dung reacted with lead acetate, forming basic carbonate, (white lead). All these operations required a careful control, be it for the production of carbon dioxide, be it for the temperature that was not supposed to exceed 40°C to avoid the formation of sulphydrates that gave the product a yellow colour. Once the conversion had gone far enough, the stack was carefully broken down and the product first ground and sieved from unchanged lead, then washed to remove any lead acetate and finally dried. All these operations resulted in the formation of large amounts of dust, which had a disastrous effect on the health of the workers. It took a month for washing, another for drying.

The process patented by Bischoff followed a different approach. As explained by Cohen, it used as raw material litharge, a readily available lead oxide. The litharge was first reduced with water gas (Mond gas) to form the black sub-oxide of lead and then damped and oxidized with atmospheric air to form lead hydroxide. The hydroxide was mixed with water containing a little acetic acid and then carbonated with carbon dioxide from the air blown of the water gas plant. Carbonation transformed the lead hydroxide into

white lead; the slurry was then filtered and the water driven out of the filter cake with linseed oil. This gave white lead paint ready for packing direct, untouched by human hand.

Mond bought the process, built a plant, and formed a company, the Brimsdown Lead Company. Initially the plant was plagued by operational difficulties but eventually these were solved and the product proven to be better than the Dutch one, although harder to use in paint applications. Ultimately the plant was taken over by Associate Lead Co., and then by Cooksons. The Bischoff-Mond process is no longer used (Cohen, 1956; Roberts, 1989).

Epilogue

In his 1889 presidential address to the Society of Chemical Industry, entitled "Necessity is the Mother of invention", Mond concluded his address with the following statement: "The statement is frequently made that "Necessity is the mother of invention". If this has been the case in the past, I think it is no longer so in our days, since science has made us acquainted with the correlation of forces, teaching us what amount of energy we utilize and how much we waste in our various methods for attaining certain objects, and indicating us where and in what direction and how far, improvement is possible; and since the increase in our knowledge of the properties of matter enables us to form an opinion beforehand as to the substances we have available for obtaining a desired result, we can now foresee, in most cases, in which direction progress in technology will move, and, in consequence, the inventor is now frequently in advance of the wants of his time. He may even create new wants, to my mind a distinct step in the development of human culture. It can no longer be stated that "Necessity is the mother of invention", but I think it may truly be said that the steady methodical investigation of natural phenomena is the father of industrial progress". ■

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