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Ludwig Mond: Vorsprung durch Technik

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Abstract

Ludwig Mond was born at Kassel in 1839. He attended the universities of Marburg and Heidelberg. His first important work was the development of a sulphur recovery process for Leblanc soda wastes. To exploit this he came to England in 1862. He joined with John Brunner in 1873 to manufacture Soda Ash using the Solvay process. After two years of struggle the partners succeeded. Brunner Mond and Co. was floated in 1881 and Mond's fortune was made. Mond went on to develop improvements for chlor-alkali manufacture and it was a chance observation during this work which led to the discovery of nickel carbonyl. He used this to build a plant for the purication of nickel. Mond used his wealth to help scientific research notably through the Royal Society and the Royal Institution in London. He died in 1910. He had two sons, Robert a fine scientist who extended his father's work, and Alfred who became the first chairman of I.C.I.

In August 1888 Ludwig Mond and his partner John Brunner were successful men. The ammonia-soda process, which they had licensed from Solvay, had in their hands been transformed from a small scale enterprise to a major and highly profitable industry.

Brunner was destined to remain in Mid-Cheshire to dominate the company and to become a substantial land owner and the complete Cheshire county gentleman. Mond, by contrast, although he remained a senior director of Brunner Mond and Co. was to appear less and less on the Winnington scene. His restless energy was to be devoted to other enterprises. His main residence was to be London with also a house in Rome. He was to remain to the end of his days the European man of science and culture. Patron of science and the arts, he gave financial security to the Royal Institution in London, played a key role in the affairs of the Royal Society and was a noted connoisseur of paintings and music. Although he became a British citizen and did much for his adopted country he retained a strong German accent, his household was run on German lines and he combined his business success with culture in a way which was quite alien to fashionable London society of his day.

All of this was along way from 7 March 1839 when a son, Ludwig, was born to Henriette (neé Levinsohn) and Moritz Mond in the town of Kassel. The Mond family were moderately successful but it was the Levinsohn connection which was to be more important in forming the young Ludwig. His mother's sister was married to Adolf Löwenthal who had a business in electroplating in Köln. Mond was to serve part of his apprenticeship with this business but of much greater importance to him was the daughter of the family Frida Löwenthal, who although eight years his junior, became engaged to him in secret at the age of 13 and was to support him throughout his life. Frida was no ordinary young girl. She had a fine mind and an intense serious disposition. Ludwig Mond's biographer [1] describes how as a 15 year old she taught herself Italian so that she could read scientific journals in that language to help Ludwig. She also used to help him with his experiments in the upper store of the Löwenthal house. As these were mainly devoted to the oxidation of sulphur compounds, the household must have been very tolerant! But this is a digression. The main theme today is Ludwig Mond scientist and technologist.

The organisation of education in Germany in the 19th century is not a subject on which I have much knowledge. It must, however, have had a high degree of tolerance for the unusual individual at least in its upper reaches. Reading the story of Mond's early years in Cohen's biography [1] one can only conclude that the young Ludwig was not so much difficult as impossible, but talented with it. His early education was at the Realschule in Kassel, from which at 14 years he moved to Kassel Polytechnik. Here, it is recorded, he was introduced to higher mathematics, physics, theoretical and technical chemistry, mineralogy, geology, botany, zoology, engineering, architecture, machinery and mechanical drawing. All this before he was $16\frac{1}{2}$ years, when he moved on to the University of Marburg where Kolbe was a professor. From there he moved to study with Bunsen at Heidelberg. By Easter of 1858 at the age of 19 years he concluded that he was educated. So without a degree or indeed any formal qualification he left. He was considered by his teachers to be an able pupil and apparently this type of self planned education was not all that unusual. If the extent of his studies seems large, Mond apparently found time for other activities. He became a passable violinist and had a good baritone voice. He was a skilled duellist although he gained a fair number of scars which he kept hidden behind his large black beard. His father, it is recorded, like all father's warned him of the perils of tobacco and alcohol with the usual lack of effect. And he left Heidelberg in debt. None of this apparently dented his self confidence as he set out to earn a living in the chemical industry but with a clear plan to become one day the master of his own enterprise. It was to take nearly twenty five more years but he eventually made it!

It is recorded that as a young boy watching his mother darning socks, he asked her what had happened to the wool where the hole was. The idea of the energy and mass balance and the recycling of waste products were to be the main themes of his life in technology. He gained his early experience of chemical industry firstly with his uncle Adolph where he suggested methods for the recovery of $ZnSO_4$ and nitric acid from electroplating waste liquors. He worked with a wood distillery near Mainz where lead and copper salts were also made and, in what was to be a formative move, in 1860, at 21 years old, he joined a Soda factory at Ringenkul. Cohen, in his biography, describes this period of Mond's life and outlines some of his schemes for profit improvement by raw material recovery. Mond was clearly an optimist. He would cost his processes on the base of a few laboratory experiments, 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. He, nevertheless, was building up a reputation and profits were made.

As the alkali industry was to be a key part of Mond's life it is worthwhile at this point to set out the key steps of the Leblanc soda process which was in 1860 the dominant process for the manufacture of sodium carbonate.

$$2NaCl + H_2SO_4 \longrightarrow 2HCl + Na_2SO_4$$

$$Na_2SO_4 + CaCO_3 + 2C \longrightarrow Na_2CO_3 + CaS + 2CO_2$$

The energy input is the carbon used in the second reaction, while sulphuric acid is degraded to the useless calcium sulphide. Sodium carbonate, or soda ash as it was known commercially, was separated from calcium sulphide by dissolution in water followed by evaporation, and finally heating to dryness. The waste calcium sulphide, a foul smelling sludge was dumped, a practice which made digging the ground near old alkali works an unpleasant and often dangerous job. The first reaction too had its environmental problems as the HCl produced was at first just allowed to escape up the chimney. It is an interesting comment on the logic of the British law makers that the ALKALI ACT was introduced to control the emission of HCl.

Mond, while working for the Pfeiffer and Schwarzenberger soda fabrik, set about on his own account to develop a process for the recovery of S from CaS. It was these experiments with which the young Frida Löwenthal was a laboratory assistant. A job which amongst other things involved keeping away stray cats which were attracted by the smell! It was at this time that Ludwig (22) proposed to Frida ($13\frac{1}{2}$ years old) in secret.

The process involved, in the first place, was the oxidation of dry CaS in air followed by extraction with HCl to leave a residue of S. Given the complexity of the chemistry of polysulphides and polythionates at different pH values and temperatures it is remarkable that anything at all useful emerged from this. None of these complexities were known to Mond and he was able to devise ways of recovering up to 50% of the S in CaS. This process was patented in Ludwig's name, the money being put up (not for the first time) by his father.

The S recovery process was offered to and accepted by a Dr. Hasenclever in Aachen and an agreement was entered into. Mond also at this time attracted the interest of a company in Utrecht and was employed by them to set up a Leblanc factory. All of this was good experience but Mond was always keen for a bigger challenge and it was clear to him that it was the British chemical industry, which in 1862, offered the greatest scope for his process.

Moritz Mond, via his textile business, had a few contacts in London and Manchester. It was on the strength of a few introductions of no relevance to the chemical industry and speaking only a little English that Ludwig set off in September 1862 (aged 23 years).

The weapons with which Ludwig Mond was to conquer the British industry were threefold:

(1) A scientific and engineering training which was the best then available.
(2) A knowledge of the Leblanc process and an embryo S recovery process.
(3) A total conviction in his own ability to succeed.

He had not at this stage taken an irrevocable step, however, and he was to keep his contacts with Hasenclever and Smits and Co in Utrecht. He did not waste his time in England. Within two weeks of his arrival he was in Widnes meeting with

John Hutchinson, who in 1847, had set up the first Leblanc soda factory in Widnes.

Mond and Hutchinson were an unlikely pair. Hutchinson was the son of a Naval Officer and from all accounts an English gentleman in the W.S. Gilbert mode. He had a dominant personality and fiery temper. So did Ludwig. Their relationship seems to have been quite a combatitive one but just about held together by mutual esteem for the qualities of the other and I suspect a strong financial self-interest by both parties. The agreement they came to was that Mond would operate his S recovery process for a payment of £300 p.a. provided Hutchinson should be able to make £450 p.a. for it. Mond retained the right to deal with other Leblanc manufacturers and this was one of the continual sources of friction between them.

Mond was as energetic in his social life as he was at work and in the Widnes area he soon attracted to himself a group of young bachelors interested in science and the arts. They would meet at various places and often at his lodgings where in true Lancashire fashion they were fed on ham and eggs (despite L.M.'s Jewish upbringing). He was also active in forming a group which was to become the "Society of Chemical Industry". He was to use the meetings of the SCI and BA to publicise his S recovery process. He would have done well in the era when publications were weighed as he managed to get his S recovery process published at least four times! In one of these [2] he wrote up his equations. As you look at these remember that as Mond worked them out Mendeleef had not yet published his periodic table and the atomic weight/equivalent weight distinction was not on a sure footing.

$$2CaS + 2HO \longrightarrow CaHS_2 + CaHO_2 \text{ (Calcium hydroxide)}$$

with O_2 for air:

$$2CaS + O \longrightarrow CaS_2 + CaO$$

$$CaHS_2 + O \longrightarrow CaS_2 + HO$$

$$CaS_2 + 3O \longrightarrow CaS_2O_3$$

at higher temperature:

$$CaS_2O_3 \longrightarrow CaSO_3 \downarrow + S$$

Thus S is taken up by alkaline CaS_2 to give polysulphides. But more air and residual $CaHO_2$ converts nearly all the S to CaS_2O_3, and finally

$$3Ca_2S_2O_3 + HCl \longrightarrow CaCl + 2CaSO_4 + HO + 4S$$

Despite this, Mond got his S recovery to work. He made money from it and by 1865 was confident enough to discuss his engagement to Frida Löwenthal with his father and their engagement was arranged in November 1865 and they were married on 10, October 1866. By mid 1867 Ludwig and Frida had set up home in Appleton, near Widnes. In October 1867 their elder son Robert was born to be followed by Alfred just one year later.

The other key event in the 1860 period was Mond's meeting with John T. Brunner. Brunner was born in Liverpool to a Swiss pastor. He was chief clerk to Hutchinsons but like Mond had a strong desire to be his own master. They were to be ideal partners. Brunner, although not technically educated, seemed to understand Mond's ideas and seemed to be able to help Mond to concentrate his mind on one thing at a time and to discard some of his more improbable ideas. He was, later, to be the partner who imposed the financial and commercial disciplines which complimented Mond's technical knowledge and drive. Their friendship grew and by 1870/71 they were trying to decide what line to take. These included a Leblanc soda factory, a S recovery plant to take in waste and sell S, and numerous others. By this time, rumours were reaching Widnes that Ernest Solvay at Couillet in Belgium was having success with the 'Ammonia-Soda' process. Mond was curious to know why Solvay was succeeding when others had failed. After all, it would be bad business to invest in Leblanc or the associated S recovery is A/S was to succeed.

In April 1872, Mond sets off for Belgium to meet Solvay. His reputation had gone before him and Solvay was clearly delighted to receive Mond. Solvay records Mond's approach to him, in bad French, as follows [3]:

> "J'exploite", me dit-il, "un procédé que j'ai inventé pour l'utilisation de résidues de fabrication de la soude Leblanc. Il est vexant de se donner autant de peine pour retirer de ces marcs le soufre qui a été introduct si peniblement dans la réaction. D'ailleurs M. Merle de Salindres, en qui j'ai confiance, m'a convaincu de l'avenir de votre procédé qui supprimera la reason d'être du mien. Dans ces conditions, je préfère fabriquer la soude elle-même et je viens pour m'entendre avec vous."

Mond, for his part, was clearly impressed by the detailed technical competence of Solvay. Solvay clearly wanted his process to be exploited in the UK but was unwilling to take the gamble of going there himself. He believed Mond would make a go of it and they agreed that Mond should have full rights to all Solvay technology for a royalty of 8/- per ton soda ash and that Solvay should not grant any other licence in the UK for less than 20/- per ton. So, with this agreement in his pocket, Ludwig Mond came back to Widnes in high spirits and he and John Brunner set out to raise money, find a site, and proceed.

Their confidence was based on some calculations by John Brunner of the relative costs of manufacture of soda ash by the Leblanc and Solvay processes. Indicating a cost of production of £7-8-3 for the production of one ton of soda ash by the Solvay process against £9-7-6 for the Leblanc process [4].

The key advantages lay:

1 Cost of salt-brine solution for A/S solid for Leblanc.
2 Fuel usage.
3 Wages.

The hidden danger was 'Ammonia loss'.

The ammonia-soda cycle of reactions is shown below:

$$2NaCl + 2CO_2 + 2NH_3 + 2H_2O \longrightarrow 2NaHCO_3 + 2NH_4Cl$$

$$2NaHCO_3 \longrightarrow Na_2CO_3 + CO_2 + H_2O$$

$$2NH_4Cl + CaO \longrightarrow CaCl_2 + 2NH_3 + H_2O$$

$$CaCO_3 \longrightarrow CaO + CO_2$$

$$2NaCl + CaCO_3 \longrightarrow Na_2CO_3 + CaCl_2$$

The source of ammonia was $(NH_4)_2SO_4$ for gas wash liquor at a cost of £20 per ton. Brunner used 1.8 cwt of $(NH_4)_2SO_4$ per ton or 0.09 ton per ton. Poor operation of the plant could easily double this and wipe out all the saving over the well-established Leblanc process. J.I. Watts [4], who became a director of Brunner Mond, also indicated the other difficulties in his account of the first 50 years of Brunner Mond:

"The chemical reactions involved in the ammonia-soda process looks so simple that there is no reason for surprise that it proved attractive to such a large number of eminent men. They do not appear to be operations that would give any trouble; but when it is understood that natural brine is not a pure solution of salt, and is apt to form scale throughout the apparatus when treated with ammonia, that lime is not always free from unburnt stone, and when put into stills leaves more or less stone to be blown out with the residues after distillation, and that damp carbonic acid gas attacks and weakens iron vessels, it will be recognised that the process, even as worked by Solvay, was not free from complications."

This was hindsight; and confidence was never a commodity in short supply when Ludwig Mond was about. The quotation which springs to mind is the one attributed to the great Russian physicist Lev Landau describing cosmologists: "Often in error never in doubt" But Mond was never slow to recover from mistakes.

Their next problem was to find a site for their plant. The main railway line from Liverpool to London crossed the Mersey at Widnes/Runcorn and followed the valley of the River Weaver to Hartford and Winsford before leaving it to go on to Crewe. The Weaver Valley was the site of the huge Cheshire brine field and had rail access to the collieries of Lancashire and North Wales and the limestone of Derbyshire. The river was navigable to ocean going boats and Brunner and Mond correctly believed this to be the ideal site for the ammonia-soda process. All they had to do was locate and buy a site and set up. So on 4 May 1872 Brunner and Mond took the train two stops to Hartford and walked the three miles up the valley to Winsford. They were offered a lease on land near Winsford but Mond wanted his own freehold. He eventually walked from Hartford in the opposite direction and passing through the salt town of Northwich arrived at Lord Stanley's estate at Winnington.

How Brunner and Mond negotiated the purchase and raised the money to get started is a story in itself. Suffice it to say that the venture capital industry of 1862 was perhaps not very different from 1988. If it looked different they did not want to know! The financial methods used are described by biographers as 'raising delicate points of law'. I suspect that they would have led to a scandal had the venture failed. As I have said before Brunner and Mond never lacked self-confidence.

By April 1873 plans were well advanced and erection of the works was due to start. Mond, with his usual optimism, expected this to be ready by the autumn. They were however ready by April 1874.

The first three years of production at Winnington have now become part of the folklore of Northwich. Despite the assistance and design of Solvay, the differing raw materials, engineering problems, and inexperienced workers the plant went from crisis to crisis. Mond virtually lived on the plant. It may be recalled that in 1874 thermodynamics was a new science in the hands of Maxwell, Boltzman and Kelvin. But to John Brunner may be given the honour of one of the most succinct statements of thermodynamic principles as will be recognised by all experimental scientists:"Everything which could break down did break down, and everything which could burst did burst".

The year 1874 saw 838 tons made at a loss of £4300 this being nearly $\frac{1}{4}$ of the capital sum invested. And some quite desperate financial manouvres were needed to keep going including loans from Solvay. By 1875 2048 tons were produced at a profit of £2405. The tide had turned and no further loss was ever incurred.

The ammonia soda process was not Mond's invention but once the initial plant was established, Mond's mind was set on technical improvement and larger scale operation. Always there was a full exchange of technical information with Solvay. A procedure which was to continue for over 100 years. Mond made significant improvements in the recovery of ammonia and larger scale industrial operation. While Solvay must have the major credit for the initial success of ammonia soda, Mond undoubtedly contributed much to the rapid increase in production.

Commercial conditions were not easy over this period as the price of soda ash fell continuously offsetting the cost savings due to increased production. However, the inherent advantages of the ammonia-soda process, once under control, enabled Brunner Mond to prosper. By 1881 they were able to raise substantial capital. Brunner Mond and Co Limited was formed as a limited company. Brunner and Mond both became wealthy men.

Mond, although joint managing director with Brunner, was not really the man to run an established enterprise. He was the scientific entrepreneur always looking to new ideas to commercialise.

Ammonia was the potential Achilles' Heel of the ammonia-soda process. The usage of 0.09 t/t make up of ammonia would as the scale of operation grew pose problems of supply. The only significant source being the waste liquors form coal-gas manufacture. In 1881 he was experimenting with a method of nitrogen fixation. This involved the reaction of $BaCO_3$ with C and N_2 to give $Ba(CN)_2$ which was then allowed to reach with steam to give $NH_3 + BaCO_3$:

$$Ba(CN)_2 + 3H_2O \longrightarrow BaCO_3 + 2NH_3$$

This was one of many inorganic gas/solid high temperature reactions. The problems with them all are materials of construction and the need to put in heat at over 1000 °C only to recover energy below 200 °C. Even Mond's optimism failed him and he never attempted to scale it up. He decided to tackle instead the more efficient recovery of ammonia for the nitrogenous compounds fixed in coal. His first approach was to apply his skills developed on the A/S process of recovering ammonia by devising a process in which hydrated lime slurry was used to increase the ammonia extracted from existing gas-wash liquors and to increase the concentration of the solution which was transported. A plant to do this was installed at Liverpool gas works and supplied the Winnington plant. Later coke ovens of a type used by Solvay were installed at Winnington. Mond felt he could do better. His idea was to find the lowest temperature at which coal could be gasified using steam/air feedstock. Work was started in 1884 and was soon successful. The key to Mond's plant was to design a suitable furnace which would not 'ARCH' in use and to devise a heat exchanger which vapourised the water and preheated air before feeding to the furnace. He installed these furnaces at Winnington and used the ammonia produced for the ammonia-soda make up and the surplus was sold [5].

In some ways this was a case of the tail wagging the dog. In order to get ammonia, he obtained much more gas. This led Mond into the field of gas heated furnaces, gas for steelmaking, and an interest in gas-engines for power and electricity. He was also conscious that using coal in this way avoided all smoke and dust problems.

This was to lead to two developments:

(1) The formation of 'The South Staffordshire Power Gas Co'.

(2) An interest in H_2 fuel cells. These H_2 fuel cells got nowhere but they were one key link strand in the chain of events which led to nickel carbonyl as it was this project on which Carl Langer started his work with Ludwig Mond.

This work also led to Mond's contacts with Dewar and studies on adsorption of gases on Pd, Pt.

The other weakness, in principle, of the ammonia-soda process by comparison with Leblanc was that it rejected all the chloride ion as $CaCl_2$. Leblanc made HCl which could be converted to Cl_2 and then bleaching powder.

There were two main approaches taken by Mond:

(1) Use $CaCl_2$ solution

$$CaCl_2 + ZnO + CO_2 \longrightarrow CaCO_3\uparrow + ZnCl_2 \xrightarrow{\text{electrolyse}} Zn + Cl_2$$

(2) Use NH_4Cl solution

$$NH_4Cl \text{ solution} \xrightarrow{\text{Evaporate or cool}} NH_4Cl \text{ solid}$$

$$NiO \longrightarrow H_2O + NiCl_2 + NH_3 \xrightarrow{\text{heat} + O_2} NiO + Cl_2$$

$$MgO \longrightarrow MgCl + H_2O + NH_3 \xrightarrow{\text{heat} + O_2} MgO + Cl_2$$

Of these the $CaCl_2$ solution proved workable and indeed was worked and for a while was profitable due to the good price obtained for the very pure Zn. Of the NH_4Cl routes the NiO route was unsuccessful, of which more later. The MgO route was used for a while by Brunner Mond more to be a nuisance to the Leblanc manufacturers than as a major venture.

It was in 1886 that Carl Langer started work on the NiO + NH_4Cl reaction in the London Laboratory attached to Mond's house. Satisfactory results were obtained by passing NH_4Cl vapour over NiO prills. When, however, it was attempted to scale up this work at Winnington, the nickel prills broke up and became very black. The black was carbon. The only source of carbon was the 'inert gas' used to sweep out NH_3 from the reactor. In the laboratory this was pure nitrogen. On the works, nitrogen and carbon dioxide were obtained from Solvay tower off gases after scrubbing out residual NH_3. This left some CO. This must be the source of the carbon. Experiments on the reaction NiO + CO soon showed that nickel promoted the reaction:

$$2CO \longrightarrow CO_2 + C$$

This then was the process used to purify H_2 from CO impurity for his fuel cell work with the extra refinement that if H_2O vapour was added the CO produced extra H_2.

In order to obtain the best conditions for getting pure H_2, the Ni/CO reaction was studied in detail over a long period. Langer having a junior assistant (Friederich Quinke) to help with the work.

There are many accounts of what happened next but I choose two, one by Langer and the other by Ludwig Mond himself, both written many years after the event. First Langer [6]:

> "Diese Versuche waren schon längere Zeit im Gange, als wir durch einen Zufall das Nickelcarbonyl entdeckten. Wir behandelten, wie schon oft zuvor, in einem Verbrennungsrohr Nickel mit Kohlenoxyd und leiteten die entweichenden Gase, um sie unschädlich zu machen, in einen Bunsen-Brenner. Mein Assistent, der diese Versuche überwachte, ersuchte mich, den Apparat abzustellen, da er früher nach Hause gehen müsse. Einige Zeit nachdem ich die Erhitzungsflammen abgestellt hatte, bemerkte ich, daß die Flamme des Brenners, in welchen das entweichende Gas einströmte, einen eigentümliche grünlich-gelbe Färbung zeigte, die stärker wurde, als sich das Rohr abkühlte. Mein erster Gedanke war, daß Arsen im Kohlenoxyd vorhanden sein müsse, da dasselbe mit gewöhnlicher Schwefelsäure dargestellt war; ich erhitzte daher das Glasrohr, durch welches das Gas in den Brenner geleitet wurde, um einen Arsenspiegel zu erhalten. Der Spiegel trat auch sofort auf, bestand aber nicht aus Arsen, sondern aus Nickel!"

Notice the first person singular throughout.

Now Mond [1]:

> "One evening in 1889, however, the assistant who usually remained behind to close down the experiment, had gone home early, and Langer himself was waiting for the flame to die down and the last of the CO to be burnt before locking up. It was the first time he had done so, and he was quite unprepared for what he saw. For as the apparatus cooled he saw, to his great surprise, the flame jet grow luminous and increase in brightness until the temperature fell below the boiling point of water, when the flame faded again. Furthermore from its usual lambent blue, the flame had turned sickly green.
>
> Ludwig Mond was at once called to witness the same phenomenon, and together they stared in silent wonder. At first both thought of the arsenic that might be present in sulphuric acid. Arsenic was known to form a volatile hydride that would tinge the flame green. But that was readily tested, a cold porcelain tile was thrust in the flame and was immediately coated with a shining mirror, not unlike, but significantly different from, the spots left by arsenic in Marsh's test; and when the neck of the combustion tube was heated a bright mirror formed on the glass and the luminosity of the flame disappeared.
>
> The mirrors were analysed and appeared to be nickel, but such was the improbability of so heavy a metal as nickel forming a volatile compound that Ludwig would not believe his own tests, and postulated an unknown element in the nickel. Both the nickel and the CO were carefully purified, but still the phenomenon occurred. It was not, one feels, until gaseous nickel carbonyl had been frozen out to a mass of needle shaped crystals that Ludwig could really believe that he had, in Lord Kelvin's words, given wings to a heavy metal."

As research students and as heads of department and professors we have all played both parts in this type of drama. I suppose that the only fair conclusion is that it was a team effort.

What happened next is an essential clue to the driving force of Mond's life. He is now in 1889 a wealthy man, the ammonia-soda process at Winnington was now an established success and his fortune was growing. He has a house in London and was now established as a collector of paintings. In the years 1887–89 the Mond's spent their winters in Italy. Although he kept in touch with Winnington at all times. Clearly he was not now the MD who was first in in the morning and last home in the evening.

On 27 February 1889 a group of Fellows of the Royal Society had written up a proposal for his election, he was President of the Society of Chemical Industry and a Fellow of the Chemical Society. He had his own laboratory in London and access to larger scale experimental facilities at Winnington and with his various collaborators was continuing to pursue a string of new technologies related to the chlor-alkali industry. He was interested in the development of gas engines and was in the process of setting up the South Staffordshire Power Gas Company to provide gas via a grid system to the Black Country. He had made a discovery of first importance to inorganic chemistry. With his energy and resource he could, if so inclined, have launched himself into this new field. He did indeed do the obvious, he determined the physical properties of $Ni(CO)_4$ and went on to prepare two carbonyls of iron $Fe(CO)_5$ and $Fe_2(CO)_9$ and much later carbonyls of cobalt and molybdenum. Even here, it seems that much of the work after 1892 was due to Robert Mond, his elder son. It is difficult now to be sure of this. It is clear for odd remarks by contemporaries recorded by their biographers that Langer and Robert Mond did not find it easy to get along with each other. Langer clearly wanted to be seen as the prime mover and Robert, to avoid argument, tended to keep his name off the papers.

In an introduction to a paper [7], written after Ludwig Mond's death, Robert Mond writes:

> "The actual researches presented great difficulties, both of a technical and theoretical nature and were ably carried out by my father's assistants Drs. Heinrich Hertz and M. Dalton Cowap, acting under my father's instructions and on my own when my father was absent."

While these contributions were significant they are only a fraction of what would have been possible if Ludwig Mond was of a mind to explore the preparative chemistry of metal carbonyls as his major task.

Mond did give one lengthy paper on Metal Carbonyls on Friday 3 June 1892 at The Royal Institution in Albemarle Street. It is of interest that having arrived at the correct representation of $Ni(CO)_4$ he was led astray by his work on iron carbonyls and proposed chain structures. Without it must be said very much evidence either way.

It was not then, inorganic chemistry which was to drive Ludwig Mond. He realised that he had here a potentially unique method of making pure nickel. A metal which was just beginning to have importance in metallurgy. Just as there was the existing Leblanc process of ammonia-soda to attack there was also an alternative nickel purification process. The Orford process which relied on the much greater solubility of Cu_2S in Na_2S than nickel sulphide. In fact it is probable that the purity obtainable by the carbonyl process was much greater than called for at the time. Mond, however, was not to be deterred. John Brunner, having been through the traumas of new technology once did not want another try. Mond tried to interest the metal processing industry of the UK but in vain. So he decided to go it alone.

Nickel occurs in nature along with varying quantities of copper and iron. Mond and Langer found that to use the carbonyl method effectively, it was necessary to remove the bulk of these impurities before obtaining a crude metal which would form the carbonyl readily. He further needed to discover how to control the decomposition of nickel carbonyl to give the metal in a commercially useful form. In his London laboratory, Mond and Langer set up apparatus which could produce and decompose several pounds a day. It is probably just as well that his neighbours were unaware of this!

In 1892 an experimental plant was built of the works of Henry Wiggin at Smethwick near Birmingham. This time Mond proceeded with caution with the scale up. N doubt the toxicity of CO was a cautionary factor, the excess toxicity of $Ni(CO)_4$ over and above its CO content was then unsuspected. It was in 1898, at the invitation of Mond that Dr. Roberts-Austen, a distinguished civil engineer was to write up a detailed account of the pilot plant and its operation [9]. The nickel sulphide ore was roasted in air to give a finely divided oxide which was reduced to Ni powder by water gas. The metal was kept at 50 °C by cooling while $Ni(CO)_4$ was formed and $Ni(CO)_4$ was then decomposed at 180 °C over constantly moving nickel shot which was removed once above a critical size. Life did not always work out like that and quite monstrous lumps of nickel would from time to time cause severe damage. This in essence is still the process used today.

By 1898 Mond was convinced that he had a workable process. By now he was 60 years old and his youthful vigour had left him. It would seem, however, that at half-speed he would leave most of us exhausted. Langer says that he found the work involved very trying.

To proceed further he needed a source of ore and a suitable site for the plant. Mond bought two ore bodies near Sudbury in Ontario, Canada. These were "up country" and he built there his mine, ore-benefication plant, a railway, a hydro-electrical plant and a village. He was assisted in this by his two sons Robert and Alfred and Dr Mohr but it was clear that he took the personal responsibility.

The major centre of metallurgical industry at the time in the UK was in South Wales and it was to there that Mond went for his plant site. As at Northwich for ammonia-soda, he bought an estate and manor. This time, however, it was to be Carl Langer who took up residence and lived by the plant as it was built and started up.

Here I must put in a personal note, I was invited in May by Dr. Brian Davidson, the manager of the Clydach site, to see the process as it is today and to meet some of the older pensioners of the firm. As one who had grown used to the plant and environment of Mond Division ammonia-soda factories, the impact of coming over the hill and seeing the Clydach housing and office buildings was very great. It was almost a replica of that at Winnington, the only difference was that I was received by a Welsh rather than a Cheshire voice. Even the style of engineering in the modern factory had the "Mond" imprint rather in the way of a painting by an artist of the "Mond" school.

In other respects the start-up of the plant went better than the ammonia soda experience. There was just one exception, there was an escape of $Ni(CO)_4$ and this resulted in some fatalities. This resulted in a strike, and Ludwig came near to calling off the whole operation and repaying the shareholders. Things had gone too far for that and it was Alfred Mond who personally got the show on the road once more. Like all metal related business, the nickel process has gone up and down with the market. For nearly seventy years, the process stayed much as Mond and Langer designed it. A continuous process carried out multi-stream to give reliability. In the late 1970's, INCO, the successor company to Mond Nickel, decided to re-engineer and update, and it was this which secured its survival during the economic blizzard of 1980–83. There is now a second carbonyl refinery in Canada. There are adaptations of the process to give fine powders of many different particle shapes.

The name of Mond is now assured in South Wales as the fare stage of the bus route up the valley is know as "the Mond".

For someone in his sixties this work on nickel might seem enough. Ludwig thought otherwise. Via a Professor Bischof he became interested in the manufacture of white lead. The traditional process of making this basic carbonate came from Holland and had an agricultural flavour. Lead strips were corroded in pots over vinegar and kept warm by rotting manure which supplied CO_2. Bischof started from lead oxide, reduced by Mond gas to a sub-oxide which reacted with acetic acid/CO_2 to give white lead. A more controlled, eventually, process which Mond as consultant helped to develop. He also financed the first plant. This was never a great success, due mainly to the product being harder to use in paint applications than the old, although it was demonstrably superior in skilled hands. Eventually, it was taken over by Associate Lead Co. and subsequently Cooksons. The Bischof-Mond process is no longer used.

His failure over the 1890–1909 period was undoubtedly to take no part in the electrolytic production of $NaOH/Cl_2$. In many ways he was ideally placed to do this. Brunner Mond by the early 1890's were making chlorine by the MgO/NH_4Cl route and caustic soda by the difficult Löwig process. The United Alkali Company, Brunner Mond's rivals used Leblanc and the Löwig process and HCl oxidation for chlorine. Mond decided to make his chlorine by

(1) $CaCl_2 + ZnO + CO_2 \longrightarrow ZnCl_2 + CaCO_3$

(2) $ZnCl_2$ electrolysis

This worked and indeed made money. It was limited as zinc demand was never high enough to match Cl_2. Ferdinand Hurter, a friendly rival of Mond, was a director of UAC and he gave a fine thermodynamic analysis of routes to $NaOH/Cl_2$. But for some reason insisted on taking pessimistic values for the voltage needed to produce Cl_2 and of the cost of electrical machinery. Mond it appears was influenced by this. Rather oddly, he developed a bias against electrochemistry. This appears to have come from his attachment to his carbonyl process for Ni over and against electrochemical methods. At the end of his paper on his process for nickel given to the New York section of the Society of Chemical Industry on 11 November 1895 he concludes [10]:

> "What gives me the greatest satisfaction in relation to this investigation is, that I believe that I have succeeded in working out a purely chemical process for extracting Nickel from its ores, which will be cheaper and simpler than any electrolytic process than can be used for the purpose. Of late years there has been a tendency to take chemical operations out of the hands of the chemist and thrust them into those of the electrician, in the belief that the simplest way of obtaining a chemical change consists in pulling apart a chemical compound by electrical energy and subsequently putting its constituents together again in the forms desired. I know there are many chemical operations which will always be carried out to much greater advantage by the old chemical methods and I have no doubt that newer methods will be found, of which nobody thinks at present, based upon

purely chemical reactions, such as the process which I have brought before you tonight, which will effect the chemical changes we want to produce at a smaller expense of energy than can be done by electrolysis."

This has proved true for Nickel but was disastrously wrong for $NaOH/Cl_2$. It was to be twenty years later, and after Ludwig Mond's death, that Brunner Mond finally, and at much greater expense, bought their way into electrolysis. I am glad to say that we who have succeeded him have developed the technology to a very high standard.

Of this two great efforts, ammonia-soda and nickel, it is nickel that now appears to have the brighter future. Although the ammonia-soda process still operates in Cheshire and elsewhere it is being squeezed by growing electrolytic chlor-alkali on one side and greatly expanded mining of natural sodium carbonate on the other. With a modern plant in South Wales and Canada, Mond Nickel is expanding and prospering.

Let us conclude with a few thoughts on Mond the man.

Clearly Ludwig Mond was a man of quite exceptional talent and an appetite for work. Equally clearly he did not suffer fools gladly. The folklore in the Cheshire area has many stories of Ludwig Mond and his relationship with the workforce. He was very critical of the then British habit of not wishing to work at the weekend. Clearly he became reconciled to this later in his life. It was Mond who instituted the idea of 4-shift crews working eight hours to cover 24 hours so that each had a rest. He brought in a short working week and he was one of the earliest employers to suggest holidays with pay. In all this he was supported by his partner John Brunner.

Working with Mond is described by employees who later became Brunner Mond directors and they all stressed his demanding nature but also how he would repay them by support and trust. It is in the nature of things that those who found him intolerable left no record. I suspect they were numerous.

His relationship with his sons would make a study in itself. Robert, the elder, clearly conformed to his father's wishes. He was clever, learnt easily and went on to become an excellent scientist in his own right although hampered by ill-health. Alfred and his father for many years led a stormy relationship, but Alfred it was who become the brilliant man of affairs eventually becoming a government minister, and when the wrong party was elected, played a key role in the Mond companies and eventually became the first Chairman of ICI.

Both Langer and another close associate Bainbridge, testify that Ludwig Mond was physically clumsy and a poor experimenter. Perhaps it was this which led him to seek large enterprises where he could direct others.

Although he was a wealthy man, it was a by-product of his urge of create rather than an end in itself. He was to give away a substantial fraction of his income.

For example, he funded a new building for the Royal Institution in Albemarle Street in London. Typically Mond, he did this in a curious way and one press reporter of the day claimed that:

"The R.I. is to be turned into a 'cheap labour' branch of his Alkali Works"

although this was not the general opinion. Certainly the name of Ludwig Mond is remembered with great affection even now at the R.I. and all the press cuttings of the day and his bequests are kept recorded in the Library.

He also gave substantial sums to the Royal Society and the Society of Chemical Industry.

In contrast to South Wales, where the Mond name is kept in local usage, in Cheshire it is Brunner whose name is more often attached to local institutions. For example, the "Brunner Library" in Northwich. Although until two years ago the local Division of ICI was called ICI Mond Division. A name which was lost in a recent re-organisation.

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