Friedrich · Mordike
Magnesium Technology

Horst E. Friedrich · Barry L. Mordike

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Metallurgy, Design Data, Applications

With 590 Figures

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Preface/Foreword

Magnesium was discovered and isolated as a chemical element in 1808 by Sir Humphrey Davy. The problem with its isolation was associated with its reactivity, which has haunted all those interested in using magnesium as components. The applications today must also consider the problems of corrosion. If we consider other properties e.g. elastic rigidity we find that the elastic constants are significantly lower than those of other metals. The yield strength or ultimate tensile strength is also poorer than most constructional metals.

The significant event at the beginning of the twentieth century was aviation and this changed the rules – it was the specific yield strength which was important and indeed much work was undertaken in the two wars to develop magnesium alloys for aviation. Magnesium had come of age and was used extensively in military aircraft during the Second World War. Thereafter, there was a slump in its use and apart from isolated applications was unable to compete with other metals, both from an economic and also technological standpoint.

In the nineteen-nineties a concentrated effort was made to solve many of the problems, which limited the widespread application of magnesium alloys. This effort was essentially global with producers and car manufacturers uniting so that magnesium becomes recognised as a structural material. One group was USA and Canada, another was Australia with CAST, Israel, Norsk Hydro, MEL and Germany. In this book we have authors covering all aspects of magnesium technology. For the first time in 50 years we are able to show which advances in component development have been made possible since the tome by Emley of MEL. The authors come from Germany, USA, Norway, Canada, Israel, Switzerland and the UK and have covered the following topics on a chapter or sub-chapter basis.

There have not been many books on magnesium. The first was Beck's "Magnesium und seine Legierungen", published in the 1930's, which was hurriedly translated into English. This was followed 25 years later by Emley's book, Principles of "Magnesium Technology". This was a comprehensive revue of the state of the art. Since that time there has been the ASM Handbook which provided a useful collation of the properties of magnesium alloys but did not attempt to update Emley.

There are nine chapters in this book. The first chapter covers the history until 1945 and also from 1945 to about 1990. The second chapter covers an extensive survey of 30 pages of various production technologies of magnesium. This is followed by a detailed presentation of the physical metallurgy, physical and mechanical constants, deformation behaviour, strengthening mechanisms, classification of alloys, binary and higher phase diagrams, various MEL alloys and highly creep resistant alloys. Chapter 4 is devoted to melting, alloying and refining. Chapter 5 is a contribution by several authors of 70 pages to a detailed description of present day magnesium casting alloys. Chapter 6 covers the technology of magnesium and its alloys. This chapter of 200 pages discusses many aspects e.g. sand casting, casting defects, inspection, identification and elimination of defects. This is followed by a discussion of die casting, also squeeze casting and semi-solid casting with their associated properties. Rolling of magnesium and sheet metal forming is a recent important extension to magnesium technology. Extrusion is also discussed with alloy developments and novel extrusion methods. An important topic in this chapter is magnesium matrix composites. Joining and welding processes are also covered in this chapter. Alternative processes to welding, such as adhesive bonding technology, clinching, riveting, direct screwing, folding, hybrid joining are relatively new methods of joining magnesium. Machining of reinforced and un-reinforced magnesium alloys concludes this chapter.

Chapter 7 is dedicated to corrosion and surface protection and represents a chapter in which significant advances have been made and where some problems have been eliminated. Chapter 8 shows examples of automobile applications in Europe and North America together with concepts of life cycle inventory of vehicles, other applications such as hand tools, sports equipment, electronic equipment and aerospace. Barriers to magnesium are also discussed. In chapter 9 the problem of setting up a secondary recycling strategy for magnesium is discussed.

This book for the first time shows a wide spectrum of applications. Obviously, the automobile applications are particularly important as they could guarantee that a sufficient volume of magnesium is produced; ensuring that unit prices are low. The price competition is keen and there is still much to be achieved with wrought products, in particular.

Significant advances have been made in corrosion protection, joining technologies and recycling.

Horst E. Friedrich Barry L. Mordike

Dr. Horst E. Friedrich

Prof. Dr. H. E. Friedrich studied engineering at the Technical University of Munich. After working in the engineering and consultancy sectors, he took up a senior management position in the aeronautical industry in 1986. He was responsible for new methods of construction and new materials, aircraft engines and optimising product development times. In 1996, Prof. Friedrich joined Volkswagen AG in Wolfsburg as head of vehicle research, where at last he was head of Group research for materials technology and vehicle concepts. He specialised in innovative materials and construction methods, and concept vehicles for future vehicle specifications.

Since March 2004 he is director of the Institute of Vehicle Concepts at the German Aerospace Center in Stuttgart and professor at the University of Stuttgart. The research fields are Alternative Power Trains and Energy Conversion as well as Light Weight Design and Hybrid Construction methods.

Prof. Dr. Friedrich worked as Director of the Board of the International Magnesium Association (IMA) and has a lectureship at the Technical University of Berlin for materials and design in the transportation industry.

Prof. Dr Barry L. Mordike

Barry Mordike studied Physical Metallurgy at Birmingham University and completed his studies with BSc(Hons) Class1 in 1956. He then undertook research for his PhD in the Cavendish Laboratory, Department of Physics, University of Cambridge, completing his PhD in Summer 1959. He then continued research in the Institut für Metallphysik, Universität Göttingen as 'Wissenschaftlicher Assistent' to Prof. Peter Haasen. In September 1966 he took up a post as Senior Lecturer (C4 Professur) in the Department of Metallurgy, University of Liverpool, where he stayed until the end of1976.In Dec 1976 he was appointed to the newly created Chair of Materials Engineering and Technology at the Technical University of Clausthal. He remained at Clausthal until he became Emeritus Professor in October 1999.

Apart from his academic pursuits he created in 1989 a technology transfer company, Zentrum für Funktionswerkstoffe g.G.m.b.H(Clausthal) with the aid of Government funding. This enabled projects to be completed where industrial competence and confidentiality were necessary. In 2002 Prof. V. Neubert took over from him as General Manager.

Initially, his research interests concentrated on fundamental problems such as deformation processes, initiation of fatigue, crystal growth, strengthening mechanisms in metals. He changed his emphasis and developed interests in more applied research. Prior to going to Clausthal he started to work on magnesium alloys (1972), some aspects being supported by MEL (Elektron), Powder Metallurgy (1973) and Laser Technology (1976). At Clausthal, he rapidly built up a considerable research potential and covered a wide range of subjects.

The period 1976 to 1999 will be remembered for its contribution to developing Laser Treatment of Materials, Magnesium 1972 – present day, Powder Metallurgy and Composite Materials, Surface Engineering, in particular, Plasma Immersion Technology.

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Contents

1 History

1.1 History until 1945

Kurt Harbodt

The history of elementary magnesium started in 1755, when Joseph Black, a Scottish chemist, discovered that magnesia contained a new element, magnesium. Black was unable to isolate this element.

Magnesia had previously been known as "white stone" or "white earth" (magnesia lithos or magnesia carneus). It is generally accepted that the name originates from an area in Thessaly, Northern Greece, where in ancient times the material had been excavated and exported to countries around the Mediterranean.

Actually, the British chemist and scientist Sir Humphrey Davy is honored as the discoverer, because it was he who isolated the metal in 1808, when he decomposed wet magnesium sulphate by electrolysis using a voltaic cell and a mercury cathode.

Exactly 20 years later the Frenchman Antoine Alexandre Brutun Bussy isolated the metal by fusing dehydrated magnesium chloride with potassium at elevated temperatures.

Then Michael Faraday, the famous British scientist and a former assistant to Sir Humphrey, reduced dehydrated magnesium chloride by electrolysis and obtained pure metallic magnesium in 1833.

A German, Robert-Wilhelm Bunsen, after having developed the carbon-zinc electric cell in 1841, produced metallic magnesium in 1852, also starting from fused and dehydrated magnesium chloride.

Besides smaller attempts in some European countries (see below), magnesium found steady interest only in Germany, which, in 1868, was the only producer in the world, using the metal mostly as powder or ribbon for flashlights and other pyrotechnical purposes, and as a reducing agent in the production of aluminum.

As future developments and activities varied considerably in different parts of the world, we will now present the history according to country and continent.

1.1.1 Asia

In Japan Riken Metal Manufacturing Co started magnesium production in 1931. Negotiations between IG Farben, UBE Industries, Mitsubishi Shoji Kaisha and

Sumitomo Copper and Steel Rolling Works in Osaka did not result in a licensing agreement.

In 1938 a licensing agreement between IG Farben and the Japanese companies Mitsui Bussau Kaisha and Denki Kagaku Kogyo KK was negotiated to produce magnesium through thermic reduction based on [1] in the territories of Japan, Korea, Mandschukuo and Formosa. As a copy of the final contract couldn't be found the result is unknown, but during World War II six producers are reported in Japan, one in Formosa (Taiwan) and one in Korea, three using magnesite from Korea and Mandschukuo the others sea water as raw materials. The total yearly production was estimated at approximately 3,000 tons per year.

In 1952 a Japanese delegation again approached Bayer Leverkusen, one of the successors of IG-Farben, and showed interest in the silicothermic process. It is known that between 1978 and 1993 producers like Furukawa, UBE and Japan Chem and Met used silicothermic processes (Pidgeon and Magnetherm) for the production of metallic magnesium.

1.1.2 Australia

The US Bureau of Mines circular 8201 reports a magnesium production of averaging 255 t for the years 1940–1944 and 855 t (average) for the time 1945–1949. Broken Hill Proprietary Company (BHP) used the process of Murex Limited of Rainham in Essex, England. This process used calcium carbide to reduce calcined magnesite. It was a 1,000 ton plant, but never reached full capacity.

1.1.3 Europe

In Austria F. J. Hansgirg developed the carbothermic process, a direct reduction of MgO by coal. The patent [2] was granted to Österreichisch-Amerikanische Magnesit AG, an affiliate of American Metals Corporation (ALCOA group).

The pilot plant at Radenthein never became efficient because of the great amount of subsidiary equipment necessary and the dangerous handling of the pyrophoric Mg powder.

In 1938 IG Farben planned, together with the Austrian Donau-Chemie Vienna, the building of a 20,000 tons per year magnesium plant at Mossbierbaum. Before completion the plant was destroyed by bombing.

An agreement between IG Farben and Österreichische Magnesit AG, now located in Munich, was reached in 1940 concerning the further development of the carbothermic process.

In France a small production was started in 1857 by Deville and Caron. They replaced potassium by metallic sodium and added calciumfluoride.

In 1915, during World War I, the Société d'Electro-Chimie et des Aciéries Electrique began producing magnesium at Clavaux, Isère, and in 1922 Alais, Froges et Camerque (later Pechiney) built a plant at Epierre, Savoie. The latter company together with Ugine, founded, in cooperation with IG Farben, the Société Géneral du Magnesium in 1931, which set up plants in St. Auban and Jarrie. The production of these plants during World War II averaged 3,000 tons per year. After the war the Auban plant was closed but Jarrie remained in operation until 1963 with a yearly output of about 1,500 t.

A unit for reduction of magnesia with calcium carbide by the Murex process was also exploited in 1942–44 at the plant of Societe des Produits Azotes at Lannermezan (Hautes-Pyrenees).

Germany, without doubt, was the country where the development of magnesium found the greatest interest and support.

On 9 April 1885 Aluminium und Magnesiumfabrik Hemelingen, near Bremen, was founded and started production of magnesium in 1886, applying the Graetzel cell [3] to produce aluminum and magnesium in an electrolytic process. Carnallite ($MgCl_2$ KCl) was used as raw material and $MgCl_2$, NaCl and KCl served as electrolyte (42% $MgCl_2$; 32% KCl; 26% NaCl). Direct production of aluminum could not be achieved by this process but the magnesium was used partly to reduce cryolite (Na_3AlF_6) from Greenland. The total magnesium production between 1886 and 1890 was 60 t while only 39 t of aluminum were produced.

In 1873 the German government in Berlin issued a first regulation, called "Regulation for the Protection against Fires involving powders of Magnesium, Aluminium and their alloys in Foundries, Warehouses and other works".

Another electrolysis unit was built at Bitterfeld in 1896 by Chemische Fabrik Griesheim Elektron, which acquired the Graetzel process. The production ran until 1928, when the IG Farben or Oxychloride process was invented.

It was Griesheim that created the brand name Elektron on the occasion of the Air Fair at Frankfurt in 1909, a name later used extensively by IG Farben throughout the world.

In the same year G. Pistor and P. Rakowics of Chemische Fabrik Griesheim received a patent for an Al and Zn bearing alloy for structural applications (AZ). The US [4] was granted 26 July 1910.

On occasion of the International Air Transport Fair (ILA) at Frankfurt in 1909 (Fig. 1.1) this alloy was presented, accompanied by a 75HP Adler airship motor with a magnesium crankcase. The part had been cast by Elektron Co. GmbH at Spandau (Berlin).

Until 1915 Germany remained the sole producer of magnesium, mainly for military and pyrotechnical purposes. This fact was the reason why magnesium was called "the German metal". In 1900 the production amounted to 10 t.

In spite of the high energy input of 35–40 KWh/kg the consumption boomed during World War I because of the high need in military ordinance such as flares, tracer bullets and aircraft parts. World production rose from 320 t in 1915 to 1,200 t in 1918; with Germany increasing output from 80 to 500 t.

The establishment of a new company in 1925 named IG Farben also included Messrs. Griesheim Elektron and the new group took over the magnesium production at Bitterfeld in 1927.

1928 the new IG Farben- or Oxychloride process decreased the consumption of electricity per kg of Mg considerably and led to a surplus of very pure chlorine that could be used in IG's chemical business. Large-scale production started in 1931 in Bitterfeld, using brown coal as the energy resource and the brines from the nearby potash mine at Staßfurth as raw material. Production there rose from 1,270 t in 1933 to 4,000 t in 1940.

Fig. 1.1. Magnesium pavilion of the "Chemische Fabrik Griesheim-Elektron (CFGE)" at the International Air Transport Fair (ILA) in Frankfurt, Germany (1909)

In 1924 magnesium alloys (AZ; 2,5–3,0% Al; 3,0–4,0% Zn) were used for the first time as pistons in automobiles, the pistons being die cast by Elektron Metall Bad Cannstatt (the company in Berlin had been acquired by the Mahle group). Henry Ford, while vacationing in Baden-Baden, visited these die casting facilities in 1930 and arranged further discussions with Ford's executive vice president, Mr. Wibel.

A number of magnesium parts were used in airships, such as:

- Bow point, holding the mooring on the ship's side, connecting all girdles
- Piece on the cabin of command, holding the anchor cable sheaves of pulleys
- Fittings of the steering gear and fuel distribution
- Cabin tables, easy chairs, plain chairs, doors, ladders, etc.

Magnesium castings were introduced into cars on a larger scale by Professor Porsche. One of the first applications was in the 8-cylinder, air-cooled Tatra motor, produced in Nesselsdorf, Czechia. Later, Porsche worked for Austro-Daimler in Vienna and then founded his own engineering office in Stuttgart on Kronenstraße (Institut für Maschinenelemente), where he was asked to design the famous Volkswagen beetle, which contained at least 20 kg of magnesium. For the production of this car, a new city was founded in 1938: "City of the KdF-car near Fallersleben". The name was changed to Wolfsburg in 1945.

On 3 June 1933 a German Patent [1] for the continuous production of metallic magnesium through thermic reduction was granted to IG Farben which applied, in 1935 and 1936, for some amendments, including the reduction with silicon, which led to the patents 689122, 689712, 670714 and others.

The German government, heavily arming its forces and trying to depend on national resources, encouraged and financially supported the increase in the production of magnesium. Many cast parts were used in military vehicles and airplanes, but the metal also found uses in flares and incendiary bombs.

In 1934 the German Ministry for Air Transport financed a new IG Farben production facility at Aken near Dessau. The loan had to be paid back by 0.10 RM/kg magnesium delivered. This biggest plant had a capacity of 7,400 t in 1935 and ended with a capacity of 9,800 t in 1940.

In 1935 the German company Wintershall, after 6 years of research, started production at Großheringen, using fused carnallite (KCl; $MgCl_2$ 6 H_2O). The name of the process was MAGNEWIN. Production: 2,000 tons per year. As Wintershall had problems achieving the by-product chlorine in an appropriate purity and concentration a licensing agreement with IG Farben was drafted in 1944. In this agreement Wintershall was limited to a maximum production of 7,500 tons per year.

In 1939 the Staßfurth plant of IG Farben started production with an initial quantity of 3,580 t metal produced. In this year the German production was approximately 18,000 mt with a total world production of 30,000 t. (England 5,000 t; France 2,000 t; Italy 500 t; Japan 1,500 t; USA 2,500 t; USSR not available).

In Great Britain magnesium was first produced in 1864 by John Mathey of Penticroft with his Magnesium Metal Co. Ltd. in the town of Salford near Manchester. The small scale production ceased in 1908.

Major C.J.P. Ball, later founder of MEL, first became acquainted with magnesium for structural applications during his service as an officer in the army of occupation in Germany after World War I.

He, with his company F.A. Hughes & Co. Ltd., began, by an agreement with IG Farben, to explore the British market in 1920. In 1922 he convinced Sterling Metals Ltd of Coventry to start experimental work for sand castings with Elektron Metal.

After corrosion resistance and other properties had been improved considerably in 1926 by adding Manganese to alloys the Air Ministry granted the first DTD specification no. 59.

A regulation set in operation in 1928, licensing commercial vehicles by weight, led to an increasing demand of magnesium parts like crankcases, gearboxes and axle casings.

Two other companies, Birmingham Aluminium Casting Co. Ltd. and J. Stone & Co. Ltd. of Deptford joined Sterling Metals in 1929 and 1934, respectively.

An agreement between IG Farben and Hughes & Co. London/James Booth & Co. Birmingham was finalized, concerning “wrought products” including pressings and forgings.

In 1927 IG Farben was approached by the British government, which expressed its interest in building a magnesium production plant in the UK. So in 1933 IG Farben transferred the patent rights for the production and the fabrication processes to Hughes & Co. Ltd.

Founded in 1934, Magnesium Elektron (MEL) built and operated a magnesium production plant from 1936 in Clifton Junction under license from IG Farben with an initial capacity of 1,500 t.

The British government, in 1936, acknowledged the importance of magnesium for airplanes and other military applications and asked MEL to increase capacity. New negotiations with IG Farben began before the startup of Clifton Junction to increase the capacity by 2,500 t – Clifton Junction II – this new capacity coming on stream in 1938. Later, another production site was added at Lowerhouse near Burley (Basic Magnesium, Inc.).

At the beginning MEL used Greek magnesite as raw material but in 1939, when war became imminent, magnesia was extracted from sea water (British Periclas Ltd., Hattlepool) and dolomite substituted for the magnesite. That is why MEL claims to be the first company in the world using sea water as a source for raw material.

In 1936 Murex set up a 1,000 t production at Rainham based on the carbothermic process, but by coal replaced by calcium carbide as the reducing agent. Later, after being instructed by the government, it built an additional plant at Moss End, Larnak, with a capacity of 5,000 t which came on stream in 1942.

The carbothermic Radenthein process also was applied by Magnesium Metal Co. in their plant at Swansea but never reached planned capacity.

Technical difficulties also prevented production at capacity (5,000 t) in the plant erected by International Alloy Ltd. at Cardiff between 1940 and 1943. Here, aluminum and ferrosilicon was used as the reducing agent.

All plants in Germany were closed after the war with the exception of Magnesium Elektron. This company produced about 80% of the British magnesium during the war and still is an important producer, particularly active in special alloys.

In Italy 1935 SAMIS (S.A. Magnesio Italiana Sulcis) built a plant in San Giovanni Suergin/Sardinia, using the electrolytic Blumenfeld process. The first owner was G. Caproni, an industrialist in the aircraft industry. The company was later taken over by S.A. Nazionale Cogne, a state owned company. Production: 500 tons per year.

According to an agreement between IG Farben (via ELSA) and Cogne in January 1939 the production in Sardiana was closed down and a new production established in Aosta.

IG received 47% of SAMIS, its affiliate ELSA another 4%. Planned was a silicothermic process with rotary furnaces. In 1942 the company was asked by the government to increase production to 600 tons per year.

In 1939 Società Magnesio e Leghe di Magnesio started production in Bolzano, applying a silicothermic process developed by Amati and later simplified by

Ravelli. The raw material was dolomite. Production during the war approached 2,000 tons per year.

In 1942 IG Farben, Cogne and SAVA founded Compagnia Industriale del Magnesio Anonima (CIMA) for an electrolytic production in Chioggia. The project never was realized.

In 1935 a delegation from Norsk Hydro visited the German Ministry of Economy in Berlin and asked for a licence to produce magnesium, using the excess electric power available. The proposal was rejected because IG Farben did not want to have a competitor producing the metal mainly for export.

In May 1937, Norsk Hydro while visiting the Marine Chemicals Company San Francisco showed interest in the DOW process.

In 1941, after the occupation of Norway by the Nazis, the "Reich" confiscated the Norwegian aluminium industry, most of the companies being affiliates of foreign owners.

Mr. Koppenberg from Junkers was established as "trustee".

In January 1941 talks started between the Norwegian attorney Bjarne Eriksen (representing Norsk Hydro-Elektrisk Kvaelstofaktieselskab Oslo, A/S Rjukanfos and A/S Svaelgfos) and Mr. Haefliger of IG Farben to found Nordisk Magnesium Elektron Aksjelskap, with an estimated investment of Nkr 30 million.

The German Ministry of Air Transport (Air Force), wanting to hold control on such a company, turned down the project and instead, via the Bank der Deutschen Luftfahrt, founded Nordag in Oslo which, together with IG Farben and Norsk Hydro, founded Nordisk Lettmetall in Herøyen. Alumina, Aluminium, Cryolite, Chlorine and Magnesium were produced by this company. The power had to be delivered by Norsk Hydro, which had a majority of Norwegian, British and French shareholders.

In a very controversial discussion between the German Ministry of Air Transport and the German "trustee" in Berlin on 30 April 1941 IG Farben succeeded that the foundation of Nordisk Lettmetall was realised in accordance with Norwegian law and that the Norwegian partners were not forced but could participate only voluntarily. IG also reached an agreement that the French shareholders were not excluded from the necessary capital increase by a German governmental act (refusal of a currency transfer permit) but, in an arrangement with the French Banque de Paris et Pays Bas could sell their options to IG Farben at a fair price.

Nordisk Lettmetall was founded in Oslo on 2 May 1941 with a capital of Nkr 45 million. The chairman of the supervisory board was Dr. Axel Aubert, president of Norsk Hydro. The executive board consisted of Dr. Moschel from IG Farben as president, Bjarna Eriksen, vice president legal and Dr. Alf Bryn, vice president administration.

A 10,000 tons per year electrolytic magnesium plant and a 12,000 tons per year aluminium plant were later planned. The raw material for magnesium would be magnesium carbonate extracted from sea water through precipitation with lime. Before magnesium could be produced the allies destroyed the work under construction in 1944 by bombing.

Russia in 1930 acquired a licence for the production of aluminium from Pechiney. In this agreement the French committed themselves to transfering the knowledge of producing magnesium. This transfer should have been completed in 1932. The first magnesium production started in 1936 at Solikamsk in the Perm Region of Russia and production reached during World War II, 5,000 t, produced in three plants: Solikamsk, Avisma and Zaparoshe in the Ukraine.

Talks between the Russian embassy in Berlin and IG Farben/Ministry of Economy in 1941 to license the magnesium processes (electrolytic and electrothermic) under a "works support agreement" had been discussed on the occasion of a lunch on 19 May 1941 with the result that "at present the parties are not in the position to sign a licensing or works support agreement".

Switzerland saw the start of magnesium production in 1926 at Société pour la Fabrication du Magnesium at Martigny-Bourge. This was a 250-ton-per-year plant when built and it was expanded to an output of 700 tons per year in 1944 and shut down in 1947. Production was restarted in 1953 and it produced about 300 tons per year until 1959 when it was closed.

1.1.4 North America

During World War I eight companies in North America were producing magnesium; after the war the number dropped to two, both in the US: Dow Chemical using the Dow electrolytic process and American Magnesium Corporation (Alcoa) using the fluoride process.

In Canada Shawinigan Electro Metals Co. in Shawinigan, Québec, ran a production from 1915 to 1919, using magnesite from Kilmar, Québec. Energy consumption of this process was a staggering 50 KWh/kg. An ingenious Norwegian, Christian Backer, was general manager. He later founded the Norwegian company De Norske Saltverker AS to produce magnesium and extract salts from seawater in a village outside Bergen/Norway.

One of the most significant achievements in the production of magnesium was the development of the Pidgeon process by the Canadian scientist Lloyd M. Pidgeon in 1939, who based his work on former IG Farben patents. This silicothermic process generated a particularly pure magnesium metal from dolomite.

In 1941 the Canadian government funded a 5,000 tons per year plant at Haley, Ontario, piloted and brought to full production by Lloyd Pidgeon. After the war, Dominion Magnesium Co. Ltd. bought this plant. Later the operation became part of the Timminco group.

In the United States General Electric had a magnesium plant at Schenectady, NY since 1914.

The Dow Chemical Co. had put effort into magnesium since 1915. Herbert H. Dow developed an electrolytic cell, called "the bathtub." The company built its first plant in 1916 at Midland, Michigan. As raw material they used the by-product magnesium chloride from deep-well brines at Midland.

Another amongst the eight companies producing magnesium during World War I was Aviation Material Corporation at Niagara Falls, NY, later known as American Magnesium Corporation (AMC).

Those two companies, Dow and AMC, remained the only producers after the war, with Dow having a more efficient and cheaper production process.

As in the 1920s the US magnesium industry was protected by the prohibitive import duties of the Fordney-Mc-Cumber tariff and, with Dow owning all process rights, IG Farben looked for its own production in the US. They joined forces with AMC (ALCOA group) and founded the Magnesium Development Company (MDC) on 23 October 1931, with IG Farben being a 50% shareholder. But ALCOA used this agreement only strategically to reach an understanding with Dow.

Through the indirect connection with IG Farben via MDC it came to an understanding which was formalized through a cross licensing agreement between Dow, ALCO and MDC on 1 February 1934.

In this contract Dow agreed not to export to Europe before 1938 with the exception of one client, the Murex group in England. IG Farben bought magnesium from Dow (5 September 1934). Part of the agreement was also that in case of a joint production a maximum quantity of 4,000 t was allowed; a higher quantity needed the approval of IG Farben.

On 24 June 1934 a contract was signed between Dow and AMC, in which Dow committed itself to deliver magnesium to AMC at prices lower than AMC's production costs.

The cross-licensing agreement was cancelled by a US court in 1941, in a suit against those companies, being charged with "alleged conspiracy to monopolize and retrain competition in the production, use and sale of magnesium, thus violating section 1 and 2 of the Act of 2 July 1890, known as the Sherman Antitrust Law."

In the National Defense program of 1939, the US government acknowledged the great importance of magnesium alloys for aircraft and other military purposes. So it not only encouraged the industry to build new magnesium plants but also partly financed these new facilities.

Dow doubled the production in Midland in 1940 and constructed a new production plant in Freeport, Texas, partly financially supported by the British government. The 18,000 tons per year plant used sea water as the source of magnesium.

In an unbelievably short period, new capacities came on stream. Between 1940 and 1942, 15 new plants were built in the US, most of them government owned, such as those in Velasco, Texas; Austin, Texas; Lake Charles, Louisianna; Marysville, Michigan, 50% of Freeport. One of them, the 50,000 tons per year Basic Magnesium Inc at Henderson near Las Vegas, Nevada was built in less than one year as a venture between Basic Refractories of Cleveland and MEL, applying the MEL/IG Farben technology.

Other plants using the silicothermic process were in Spokane, Washington; Wingdale, NY; Dearborn, Michigan; Luckey, Ohio; Manteca, California and Canaan, Connecticut.

The Permanente Metals Co, Permanente, California (Kaiser), a partly government funded operation used the carbothermic Radenthein process, never reached the planned capacity of 24,000 t and, after having produced 11,500 short tons of ingot, ceased production. It was never reopened and was dismantled after the war, like most of the other plants.

The production in the US rose from approximately 2,500 short tons in 1939 to more than 184,000 tons in 1943, being reduced to 157,000 t in 1944 and to