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Success and Failure in the Canadian Metallurgical Industry

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Abstract

The mining and metallurgical industries are important contributors to the Canadian economy. There were successes and failures in these industries in the past fifty years. Examples of the success story of Sherritt Gordon Mines in Alberta for hydrometallurgy, the International Nickel Company in Sudbury for pyrometallurgy, the aluminum industry in the Province of Quebec for electrometallurgy, and the Bottom Blown Oxygen Converter for the steel industry by Liquid Air engineers in Montreal. The failure took place in the asbestos industry, magnesium production, the titanium pigment plant of Tioxide Canada, Noranda, and Orbite - all in Quebec, will be presented as witnessed by the author.

Keywords

Sherritt Gordon INCO; Aluminum industry; Oxygen converter; Gold, Asbestos; Magnesium; Titanium pigment; Orbite; Thompson Refinery; Tar sands; Potash; Uranium; Engineering firms

Introduction

Canada is a world leader in the metallurgical industry. The Canadian mining and metallurgical industries contribute about 40 billion dollars to national economy. Many metallurgical processes were developed or invented in Canada thanks to the new organizations that were created for these purposes:

• The Canadian Institute of Mining and Metallurgy, founded in 1898, was responsible for promoting the development of the industry by organizing meetings where academic people met industrial engineers and metallurgical processes were discussed.

• The Mines Branch in Ottawa was created in 1907 was also responsible for creating and helping many of the new metallurgical processes.

• The Canadian National Research Council founded in 1916 was behind the magnesium process discovered in Canada.

• The engineering firms created in 1947 and later were responsible for installing many plants in Canada and abroad.

Canada has also the tallest chimney in the world (Figure 1). It is located in Sudbury and is 381 m tall. Some Canadian metallurgical plants are also producing fertilizers, for example, ammonium sulfate by Sherritt and ammonium phosphate at Trail. This shows the strong relation between the metallurgical and the chemical industry. Atlas Steel in Welland, Ontario was the first in 1950s to adopt continuous casting [1].

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The industry achieved many successes as well as some failures. The successes are in the fields of hydro-, pyro-, and electrometallurgy as well as in industrial minerals such as the tar sands and the potash industries. The failures are mainly in the asbestos industry, the white pigment manufacture, magnesium recovery, and the recovery of alumina from clay [2].

Certain metals produced as by-products of main metals (Table 1). In the past few years the company names has changed (Table 2). The treatment followed here is as much as possible historic.

Table 1: By-product metals

<table>
<thead>
<tr>
<th>By-product metal or metalloid</th>
<th>Major metal</th>
</tr>
</thead>
<tbody>
<tr>
<td>Antimony</td>
<td>Lead</td>
</tr>
<tr>
<td>Arsenic</td>
<td>Copper, gold</td>
</tr>
<tr>
<td>Bismuth</td>
<td>Lead</td>
</tr>
<tr>
<td>Cadmium</td>
<td>Zinc</td>
</tr>
<tr>
<td>Cobalt</td>
<td>Nickel</td>
</tr>
<tr>
<td>Platinum metals</td>
<td>Nickel</td>
</tr>
<tr>
<td>Selenium</td>
<td>Copper, nickel</td>
</tr>
<tr>
<td>Tellurium</td>
<td>Copper, nickel</td>
</tr>
</tbody>
</table>

Kilborn Engineering

Roland Kenneth Kilborn (1902 - 1959) (Figure 2) founded in 1947 Kilborn Engineering the first major engineering firm in Canada that designed and built some of North America’s largest mines and became an industry leader in gold milling, potash refining and uranium processing. Kilborn graduated from Queen’s University in 1927 with degree in civil engineering. After two decades of working and gaining experience at a variety of mining projects in northern Ontario, he formed the engineering firm that took part in Canada’s uranium industry as well as Canada’s coal mines and washing plants, and most of the country’s asbestos mines and plants.

Kilborn Engineering also built most of Canada’s potash refinery capacity in Saskatchewan and New Brunswick. In addition, the company designed and built a number of gold mines and plants in North and South America. By 1982, the company had grown to more
than 1,500 employees, with offices across Canada and in Denver, Colorado. It is now part of the SNC-Lavalin which built the largest autoclaves in the world [see Nickel in Madagascar].

**Magnesium Thermal Process**

Lloyd Pidgeon (1903-1999) (Figure 3) is best known for the development of the process for the production of high-purity magnesium. He was born in Markham, Ontario, graduated in 1925 in chemistry from the University of Manitoba, and a PhD from McGill University in 1929. After several years at Oxford University, Pidgeon joined the National Research Council of Canada where he developed the process for the production of magnesium metal using the reaction between calcined dolomite and ferrosilicon:

![Figure 3- Lloyd Pidgeon (1903-1999)](image)

\[
4\text{MgO\,CaO} + 2\text{Si} \rightarrow 2\text{Ca}_2\text{SiO}_4 + 4\text{Mg}
\]

A group of prominent mining men from Toronto became interested in the project and raised capital that enabled Pidgeon to establish a pilot plant. Pidgeon's discovery led to the formation of Dominion Magnesium, which he joined in 1941 as a director of research. The plant is now owned and operated by Timminco. Because of the demand for magnesium during the Second World War, six magnesium plants were built throughout North America. Magnesium was used for a variety of military efforts and was considered to be the metal of choice where strength with lightness was required, as for example, in aircraft. In 1943, Pidgeon was appointed professor and head of the department of metallurgical engineering at the University of Toronto, a post he held until his retirement in 1969.

**Nosrk Hydro Process**

In Becancour just opposite to Trois Rivieres in the Province of Quebec on the western side of Saint Lawrence River, Norsk Hydro constructed a 40,000 t/y magnesium production plant in 1986 (Figure 4). It was the largest primary magnesium producer in the world based on the dissolution of imported magnesite, MgCO₃, in hydrochloric acid, evaporating the magnesium chloride obtained, and its electrolysis. It was shut down in 2006 because it was not able to compete with the Chinese companies at this time.

*Figure 4: Norsk Hydro magnesium plant in Becancour*

**MagCan**

The MagCan plant (Figure 5) north of High River in Alberta opened in 1991 at 30% of its capacity, with support from the Alberta government in an attempt to diversify the economy away from oil and gas when the price of natural resources declined sharply. It was based on chlorination of imported magnesite with chlorine and CO to produce MgCl₂ for electrolysis. It closed down after less than a year in operation. The company started its activity at a moment when the magnesium price was low. The Province provided a $103 million loan guarantee and 145 people lost their jobs.

*Figure 5- MagCan plant in Alberta*
Magnola
See “Asbestos”.

Mines Branch
The Mines Branch now called Canadian Centre for Mineral and Energy Technology, and abbreviated Canmet is responsible for the discovery and development of many metallurgical processes. One of these discovered by Downes and Bruce in 1955 is the recovery of elemental sulfur from pyrrhotite containing nickel - - a process that was applied in 2000 in Voisey Bay in the Canadian North. This marks for the first time nickel recovery from sulfides by hydrometallurgical method:

\[ 2FeS + 1\frac{1}{2}O_2 \rightarrow Fe_2O_3 + 2S \]

Nickel in the sulfide is found in solution.

Sherritt Gordon Mines
Sherritt Gordon Mines (Figure 6) in Fort Saskatchewan, Alberta is a pride of the Canadian Metallurgical industry. It produces the metals nickel and cobalt as well as the fertilizers ammonium sulfate, ammonium phosphate, and urea. It is a progressive company had its success in the collaboration with the University of British Columbia and the Mines Branch in Ottawa in the 1950s. It is also a consulting firm that built plants all over the world to produce nickel and cobalt from laterites as well as to liberate gold from refractory ores to be followed by cyanidation [3]. Sherritt also was a pioneer in powder metallurgical applications.

Ammonia Leaching Process
The process (Figure 7) is used for treating concentrates of copper, nickel, and cobalt since they form soluble ammine complexes. The process has minimum corrosion problems and any pyrite present will not be attacked. Ammonium sulfate is a by-product; it is marketed as a fertilizer. The overall reaction is:

\[ MS + nNH_3 + 2O_2 \rightarrow \left[M\left(NH_3\right)_{3}\right]^{2+} + SO_4^{2-} \]

Where M stands for Ni, Cu, and Co.

Pressure Hydrometallurgy
The company introduced modern hydrometallurgy in the world and specially pressure reactors. It precipitated nickel directly from ammoniacal solution by hydrogen under pressure instead of the long known process at that time - - the first in the world by the reaction:

\[ M^{2+} + H_2 \rightarrow M + 2H^+ \]

Crystals of cobalt were also produced by the same process (Figure 8). Example of the reactors used by Sherritt (Figure 9) [4].

Ammonia Leaching Process
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Where M stands for Ni, Cu, and Co.
Sherritt Mint

Sherritt also produced by hydrometallurgical methods 5-cents nickel coins for Canada for 40 years (Figure 10) as well as the Canadian dollar from nickel covered by a thin layer of brass (Figure 11).

Zinc Industry

Sherritt also introduced in 1980 a zinc process that made the industry independent of the fertilizer industry (Figure 12). In one step the zinc concentrate was treated with sulfuric acid and oxygen in an autoclave to produce a solution of zinc sulfate which can be electrolyzed to pure metallic zinc while elemental sulfur is produced during the leaching step thus no $\text{SO}_4^-$ and the necessity to make sulfuric acid:

$$\text{ZnS} + 2\text{H}^+ + \frac{1}{2}\text{O}_2 \rightarrow \text{Zn}^{2+} + S + \text{H}_2\text{O}$$

In the old method the sulfide ore was roasted, the calcine leached with sulfuric acid, and the zinc sulfate solution was electrolyzed to get pure metallic zinc. Sulfur dioxide formed during the roasting step is transformed to acid which was always used to treat phosphate rock to produce fertilizer. The new process freed the zinc industry from the need to produce fertilizers.

Laterites

Sherritt designed the plant for nickel recovery by pressure leaching plant for laterites in Madagascar. The autoclaves (Figure 13) built by SNC-Lavalin were the largest in the world.

Falconbridge

Falconbridge Company developed a commercial process for the treatment of a mixture of $\text{Cu}_2\text{S}$–$\text{Ni}_3\text{S}_2$ obtained by smelting a copper–nickel sulfide concentrate:
Ni$_3$S$_2$ is solubilized in concentrated HCl while Cu$_2$S is not. The leaching reaction is:

$$\text{Ni}_3\text{S}_2 + 6\text{HCl} \rightarrow 3\text{NiCl}_2 + 2\text{H}_2\text{S} + \text{H}_2$$

Cu$_2$S is separated by filtration for copper recovery, while NiCl$_2$ solution is first purified from dissolved H$_2$S by air oxidation and removal of the sulfur formed, then crystallized as NiCl$_2$$\cdot$2H$_2$O. Since it is technically difficult to reduce NiCl$_2$ by hydrogen to nickel, the chloride is first calcined to NiO then reduced:

$$\text{NiCl}_2$$2H$_2$O $\rightarrow$ NiO + 2HCl

$$\text{NiO} + \text{H}_2 \rightarrow \text{Ni} + \text{H}_2\text{O}$$

**Equity Silver**

The presence of arsenic and antimony in copper sulfide concentrates is undesirable because these metals complicate the smelting and refining of copper. As a result there is interest to remove them before smelting. A copper sulfide concentrate containing 4% As and 7% Sb is treated in British Columbia by Equity Silver Company by sodium sulfide [5]. The finely divided concentrate is leached for 16 hours at 110°C to solubilize arsenic and antimony sulfides:

$$\text{As}_2\text{S}_3 + 3\text{S}^{2-} \rightarrow 2\text{AsS}_3^{3-}$$

$$\text{Sb}_2\text{S}_3 + 3\text{S}^{2-} \rightarrow 2\text{SbS}_3^{3-}$$

After filtration, the copper concentrate is shipped to smelters. The company, however, stopped production.

**International Nickel**

**Sudbury**

The International Nickel became known as INCO then Vale is a pioneer in many extractive metallurgy processes that is became the world capital of nickel [6].

**Figure 14:** 200 years nickel in Sudbury [1751- 1951]

**Figure 15:** The system Cu$_2$S–Na$_2$S

**Figure 16:** The system Ni$_3$S$_2$–Na$_2$S

**Figure 17:** The Orford Process

**Separation of Nickel and Copper Sulfides**

The separation of Cu$_2$S from Ni$_3$S$_2$ obtained from the Sudbury ore by matte formation was a problem since its discovery. The tops and bottoms process, also known as Orford process, based on fusion with sodium sulfide was used for 60 years from 1890. It was based on the fact that Cu$_2$S is soluble in molten Na$_2$S while Ni$_3$S$_2$ is practically insoluble.
In 1950 it was replaced by slow cooling of the binary sulfides followed by grinding then a more economical flotation process (Figure 19). It was also possible to separate an alloy containing the platinum metals.

**Flash Smelting**

The invention of flash smelting for copper concentrates by Outokompu in Finland and INCO took place simultaneously in 1940s. It was based on the use of the heat generated by the oxidation of sulfides to melt the charge instead of using an extra fuel in a reverberatory furnace (Figure 20). The difference between the two was in some details but the principle was the same. The same furnace was adopted to treat copper - nickel sulfides using oxygen instead of air.

**Converter**

The company introduced in 1960s the Top Blown Rotary Converter (Figure 21) to convert directly nickel sulfide to metallic nickel instead of oxidation of nickel sulfide to oxide then reduction to metal thus shortening the treatment which is a great advantage:

\[
Ni_3S_2 + 2O_2 \rightarrow 3Ni + 2SO_2
\]

**Carbonyl Process**

The pressure carbonyl process developed by INCO permitted the production of nickel carbonyl very fast at a higher temperature (Figures 22 and 23). The carbonyl process is used for refining nickel. Nickel carbonyl is very poisonous. Carbon monoxide gas reacts with nickel for form gaseous nickel carbonyl. By this method pure nickel
Electrolysis of Nickel Sulfide

Sulfides are semiconductors and conduct the electric current. At Thompson Refinery in Manitoba INCO cast nickel sulfide white metal into anodes and by electrolysis it was possible to get pure nickel at the cathode and elemental sulfur at the anode:

Anodic reaction: \[ Ni + 4CO \rightarrow Ni(CO)_{4} \]

Cathodic reaction: \[ N_{2}^{2+} + 2e \rightarrow Ni \]

Thus, it would be possible to recover the metal and the sulfur directly in one step, instead of roasting the sulfide to oxide, reduction of the oxide to metal, and then casting the metal in form of anodes for electrolytic refining. In this direct electrolysis it is possible to recover the sulfur in the elemental form instead of emitting it in the form of SO₂.

Pure Nickel by Electrolysis

INCO developed a purification step to prepare pure nickel by electrolysis in a diaphragm cell. To keep impurities at a tolerable level a calculated volume of the electrolyte is continuously bled to a purification circuit. The purified solution is returned to the cathode compartment, which is separated from the anode by a porous diaphragm in the form of a box enclosing the cathode, at such a rate that a hydrostatic head of solution builds up relative to the rest of the electrolyte (Figure 24). This prevents impurity ions from diffusing into the cathode compartment.

Pressure Leaching of Nickel Sulfide

With the discovery of the Voisey Bay sulfide deposits in the Canadian North it was decided in 2005 to use a pressure leaching process to produce elemental sulfur instead of SO₂ (Figures 25 and 26). The decision was made because the Government of Newfoundland refused that the concentrate be shipped outside the Province. This is the first acid pressure leaching process for nickel sulfides and was originally developed at the Mines Branch in Ottawa by Downes and Bruce in the 1950s. The sulfide concentrate is mainly pendlandite - pyrrhotite containing 1.6% nickel.
Ammonia Leaching in Nickel Metallurgy

In 1960s INCO built an ammonia leaching pilot plant. In this plant, nickel sulfide concentrate containing about 0.8% Ni was roasted to oxide, the oxide reduced to metal, and the metal was leached with ammonia to get a solution from which nickel oxide containing 80% Ni was precipitated (Figure 27). The plant was operated for nearly a year when it was shut down because it proved to be uneconomical.

Sorel

QIT Fer et Titan

In 1955 QIT Fer et Titan in Sorel, Quebec built nine electric furnaces to partially reduce ilmenite containing 36% TiO₂ to iron and titanium slag known as Sorelslag containing 72% TiO₂ (Figures 28, 29). The slag was used to make TiO₂ white pigment. Later, the slag was upgraded to 95% TiO₂ by pressure leaching with hydrochloric acid to remove calcium and magnesium. The technology of manufacturing Sorelslag was adopted before the hydrometallurgical route for making “synthetic rutile”.

Iron Powder

A successful iron powder industry was created in Quebec next to QIT Fer et Titan (Figure 30). High-pressure water jets are used to break up the stream of molten iron. There is a need for iron powder for use in powder metallurgy applications, for welding rod coating, for fireworks, and other applications. Most iron powders are used for automobile parts which are easier to produce than by other methods (Figure 31).
Alumina and Aluminum Industry

Alumina

Although Canada is the third largest producer of aluminum in the world, all its alumina is imported except one plant in Saguenay which is producing alumina from bauxite imported from Jamaica. Any attempt to recover alumina from silicates by hydrochloric acid cannot compete with bauxite using alkaline solution because of the low tenor of aluminum in the raw material as compared to bauxite and the ease with which aluminum hydroxide is recovered from the basic solution (Figure 32). Orbite in Cap Chat in Quebec tried to obtain alumina from clay but after 5 years operation and spending $127 million has announced bankruptcy and suspended operation in 2017 [7].

Aluminum Industry

The aluminum industry was first established in Canada in Shawinigan, Québec in 1901 by the Northern Aluminum Company (now Alcan Aluminum). Over the next 5 decades, Alcan established a network of smelters and an alumina refinery in Québec and one smelter in British Columbia (Figure 33). The availability of abundant hydroelectric power led to the establishment of the aluminum industry in Canada. Canada is the world's fourth largest producer of aluminum, after the US, Russia and China.

Søderberg electrodes which caused pollution were replaced by prebaked electrodes (Figure 34), fluorine capturing systems were added (Figure 35), and pollution problems were solved by installing gas scrubbing systems (Figure 36).

Figure 32 - Alumina production from clay. Orbite process

Figure 33 - Aluminum plants in Canada. All plants are in Quebec except Kitimat in British Columbia

Figure 34 - Prebaked electrodes
Iron and Steel Industry

General

Beside the use of blast furnaces (Table 3) Canada pioneered in direct reduction processes:

- The H-iron fluid bed process as developed by Imperial Oil Company at Dortmouth, Nova Scotia

- Stelco piloted the world’s first SL/RN rotary kiln process

Table 3: Steel production in Canada

<table>
<thead>
<tr>
<th>Source</th>
<th>%</th>
</tr>
</thead>
<tbody>
<tr>
<td>Blast furnaces</td>
<td>60</td>
</tr>
<tr>
<td>Scrap</td>
<td>30</td>
</tr>
<tr>
<td>Direct reduction</td>
<td>15</td>
</tr>
<tr>
<td>Ilmenite</td>
<td>15</td>
</tr>
<tr>
<td></td>
<td>100</td>
</tr>
</tbody>
</table>

Pelletization

The iron ore industry in Quebec has advanced greatly in Quebec and the Province has one of the largest iron ore pelletization plants in the world using inclined rotating disc (Figure 37) [8].

Midrex Process

Sidbec Dosco in Contrecoeur, Quebec was one of the first to adopt the Midrex process for steel production in 1973 (Figure 38). A larger plant was installed in 1977. Oxide pellets are charged in a vertical furnace to which a reducing gas is introduced at the bottom (Figure 39). The reducing gas is a reformed natural gas. The metallized pellets are then discharged from the furnace and melted in an electric furnace to produce steel.
Oxygen in Steelmaking

Bottom Blown Oxygen Converter for the steel industry was invented by engineers at Liquid Air in Montreal. The use of oxygen accelerates greatly the oxidation of impurities. The use of a small volume of natural gas for cooling due to a cracking reaction eliminates the deterioration of refractories [9] (Figure 40). The fact that oxygen is introduced at the bottom of reactor away from slag renders the process fast and efficient. It is a success story that is used all over the world.

Ferro Alloys

Due to the cheap electric power, Quebec became the center of ferroalloys by electric furnaces (Figure 41). Ferrosilicon, ferromanganese, and ferrochromium are produced by reducing the corresponding oxide with coke. In the case of the reduction of silica sand at SKW in Becancour, Quebec it was found that silicon monoxide, SiO, volatilized then oxidized to very fine SiO$_2$ in the recovery system. Such fine silicon dioxide found application in the concrete industry. For ferroniobium see below.

Niobium and Ferroniobium

Since 1977 Niobec owned by Cambior has been producing high quality niobium in Saint Honoré in the Saguenay region. The most important niobium mineral is pyrochlore, (Ca,Na)$_2$-mNb$_2$O$_6$(O,OH,F)$_{1-n}$.$x$H$_2$O. The lattice positions of Na and Ca can also be occupied by Ba, Sr, rare earths, Th, and U. The latter two elements are responsible for the radioactivity of some pyrochlore concentrates. The ore contains 0.5-0.7% Nb$_2$O$_5$. Pyrochlore mineral is processed by primarily physical processing technology to give a concentrate ranging from 55 to about 60% niobium oxide. Ferroniobium contains 63-68% niobium is produced by the aluminothermic process.

Niobium oxide, Nb$_2$O$_5$, is generally the starting chemical for the production of other compounds. Niobium metal is produced by the aluminothermic reduction of the oxide followed by electron beam refining. Niobium powders can be produced by the reduction of potassium niobium heptafluoride (K$_2$NbF$_7$) with sodium, or by the reduction of niobium oxide with magnesium.

Uranium

Rich uranium deposits were found in Saskatchewan (Figure 42) and as a result the uranium industry is well developed in Canada. Uranium refinery is in Port Hope, Ontario. Leaching uranium ore with sodium carbonate was introduced in Canada when the ore contained acid-consuming gangue.
Gold

Canada produces about 200 tons of gold every year of which about 80% comes from 70 mines and the rest is by-product of copper and nickel production. Explanation of the cyanidation process was done in Canada when the effect of cyanide concentration and oxygen concentration were studied (Figure 43). This led to the establishment of the theoretical equation based on the formation of anodic and cathodic areas [10]:

\[
\text{Rate} = \frac{2AD_{\text{CN}^-}D_{\text{O}_2}[\text{CN}^-][\text{O}_2]}{\delta(D_{\text{CN}^-}[\text{CN}^-] + 4D_{\text{O}_2}[\text{O}_2])}
\]

Where: \( D_{\text{CN}^-} \) and \( D_{\text{O}_2} \) = the diffusion coefficients of cyanide and dissolved oxygen, cm\(^2\) sec\(^{-1}\), [CN\(^-\)] and [O\(^2\)] = the concentration of CN\(^-\) and O\(^2\) in the bulk of the solution in mole/mL, \( \delta \) = the thickness of the boundary layer, in cm, and \( A \) = the total surface area of metal in contact with the aqueous phase.

At low cyanide concentration the term [CN\(^-\)] can be neglected in the above equation and the rate becomes: \( \text{Rate} = D_{\text{CN}^-}[\text{CN}^-] \) which agrees with the experimental data. If on the other hand at high cyanide concentration the term [O\(^2\)] can be neglected in the above equation and the rate becomes: \( \text{Rate} = D_{\text{O}_2}[\text{O}_2] \) which again agrees with the experimental data.

POTASH

Canada is the world's largest potash producer and exporter. In 1943, it was discovered in Saskatchewan in the process of drilling for oil. Active exploration began in 1951. Underground and solution mining is practiced (Figure 44).

Tar Sands

Oil is now produced in Canada from tar sands in Alberta (Figures 45-48). Tar is a mixture of many organic substances, which are separated by distillation at different temperatures. The distillation residue is pitch. The tar sands of north-eastern Alberta constitute one of the largest deposits of liquid hydrocarbons in the world. The tar sands extend over an area of over \( 900 \times 10^6 \) km\(^2\) and are estimated to contain \( 126 \times 10^9 \) tons from which at least \( 35 \times 10^8 \) tons of crude oil are expected to be produced. A part
of the deposit located at Athabasca is amenable to surface mining, while the major part is expected to be available by in-situ techniques.

**Figure 45** - Tar sands

The mining method generally used is mixing the oil sand with warm water to create slurry which can be transported by pipeline to a separating vessel where the sand settles to the bottom and air bubbles form froth on the top. The bitumen froth is skimmed off, mixed with solvent, and spun in a centrifuge to remove the water and solids. The bitumen can then be processed into crude oil.

**Figure 46** - Tar sands in Alberta

**Figure 47** - Exploiting the tar sands

**Engineering Firm**

Hatch is one of the most successful Canadian metallurgical engineering firms in Canada [11]. It was founded by Gerald G. Hatch (1922-2014) (Figure 49). The company has grown from six people in one office in Toronto in 1958 to over 11000 employees in 65 offices worldwide. The company is owned by the employees. One of the recent achievements is the world’s largest tube autoclaves for processing Saudi Arabian bauxite to prepare alumina for aluminum production (Figure 50). Among the many donations offered by Hatch is the Hatch Center at McMaster University in Hamilton, Ontario (Figure 51).

**Figure 48** - Processing of tar sands

**Figure 49** - Gerald G. Hatch (1922-2014)

**Figure 50** - Tube autoclaves

**Figure 51** - Hatch Center at McMaster University in Hamilton, Ontario
Canadian Mint

Royal Canadian Mint (Figure 52) founded in 1901 operates a technically advanced refinery in which it refines precious metals from a variety of sources including primary producers, industry, recyclers and financial institutions. The Mint refines raw gold to 995 fines through the Miller chlorination process. The gold is then cast into anodes for electrolytic purification to 9999 fine using the Wohl will process. On metallurgical events the mint issued a commemorative coin on the occasion of 250 years of the first Canadian iron making plant at Saint Maurice in Quebec (Figure 53).

Figure 52 - Royal Canadian Mint in Ottawa

Figure 53 - Commemorative dollar on the occasion of 250 years of Forge Saint Maurice the first Canadian iron making plant

Asbestos
Exploitation in Quebec

Although known in ancient times it has been first discovered in economic mines in 1876 in Thetford Township in Quebec [12]. The exploitation was simple and the workers often inexperienced (Figures 54-56) but by 1895 mining started to be mechanized. This marks the beginning of a stage of unprecedented growth. The number of workers grew with the demand for asbestos.

Figure 54 - Early mining of asbestos in Quebec

Figure 55 - Crushing room at Johnson Mine in Quebec, 1900. Note the girls were using hammers to crush the ore

Asbestos is recovered from the crushed and ground rock by aspiration (Figure 56). The air-tight building housing the equipment is under slight pressure to make sure that no fibers are released in the work place. This is done by re-circulating the clean air sucked by the fans at the top of the building through air-pressurized rooms.

Figure 56 - Recovery of asbestos fibers from the rock
Uses

Asbestos is an industrial mineral of great economic importance. About 70% of the asbestos is used in the fabrication of asbestos cement whereby the fibers are slurried in water with Portland cement for making pipes and other construction materials (Figures 57-60). Such material contains 12 - 15% of asbestos which increases greatly its resistance. Asbestos in admixture with plastics and asphalt enters in the manufacture of a variety of tiles and sheets used as a covering material.

Figure 57- Asbestos cement pipes

Figure 58 - Asbestos panels for roofs

The growing railroad industry was among the first to make extensive use of asbestos in refrigeration units, as insulation for pipes, boilers, and fireboxes (Figure 55). Ship builders also made extensive use of asbestos material. It was also used in the building industry as wall insulation, for floor and ceiling tiles, in exterior siding, and in roofing.

Figure 59 - Asbestos articles for insulating materials

Because of its heat resistance, asbestos mixed with metallic fibers and resins to the extent of 40% is used in the manufacture of what is called friction materials, e.g., brakes for motorcars and aeroplanes (Figure 56). Asbestos also enters in the manufacture of certain industrial paper and gaskets. Asbestos was also used for the brakes in the elevators in skyscrapers.

Nationalization

As Minister of Natural Resources in 1976, Yves Bérubé (1940-1993) (Figure 61) presided over the creation of State Corporation for Research, Prospection, and Promotion of Asbestos. In 1978 the National Society of Asbestos was created as a Quebec Government organization located in Sherbrooke, Quebec. The Society had a Research Department directed by Jean Marc Lalancette, Chemistry Professor at the University of Sherbrooke. In 1980 the Quebec Government decided to nationalize the industry.

Figure 61 - Dr. Yves Berube (1940-1993)

Carcinogenic Mineral

The nationalization of the industry was followed by a campaign against asbestos as a carcinogenic mineral resulting in a drastic decreased production. It was at the turn of the twentieth century that researchers began to notice a large number of deaths and lung problems in asbestos mining towns. In 1917 and 1918, it was observed...
by several studies that asbestos workers were dying young. In 1924 a woman had been working with asbestos since she was thirteen. She died when she was thirty-three years old, and an English doctor determined that the cause of death was what he called “asbestosis”.

Because of this, a study was done on asbestos workers in England. Twenty five percent of them showed evidence of asbestos-related lung disease. Laws were passed in 1931 to increase ventilation. In the 1930s major medical journals began to publish articles that linked asbestos to cancer. The use of asbestos was at its highest in the 1940s to 1970s. The warnings and regulations of the 1970s and beyond put an end to much of the production although the industry greatly improved its operation with respect to ventilation and dust control. Its use was banned in many countries.

Research towards Asbestososis

Chrysophosphate

The Research Center of Societe National de l’Amiante in Sherbrooke, Quebec developed in 1980s a process for decreasing the toxicity of asbestos by treatment with vapours of POCl3 (Figure 62). The product was known as Chrysophosphate. The process was uneconomical and technically unsound. Treatment of asbestos with phosphate ion in aqueous solutions was found to have the same effect:

\[ 3\text{Mg(OH)}_2 + 2\text{HPO}_4^{2-} \rightarrow 6\text{Mg}_3(\text{PO}_4)_2 + 4\text{OH}^- + 2\text{H}_2\text{O} \]

Figure 62 - Chrysophosphate pilot plant in Sherbrooke

Coloring with organic dyes

Chrysotile asbestos has the advantage of a large surface area and can be coloured by organic dyes. The appearance of new peaks in its X-ray diffraction patterns and in infrared spectra of the dyed product together with the absence of precipitates supports that chelates are formed with its Mg(OH)$_2$ component. Some organic compounds, e.g., bromocresol purple and phenolphthalein, although they are not dyestuffs, they color asbestos. It was found that some dyes, e.g., Thiazol Yellow G and Trypan Blue decreased the toxicity of the fibers. Unfortunately, the project was abandoned due to lack of financing, retiring of the inventor, and departure of the chemist doing the job. At that time all financial efforts were directed to the attorneys defending the case with the US Environment Agency.

Asbestos Tailings

Asbestos tailings became also a problem because to produce one tonne of asbestos about 30 tonnes of tailings have to be discarded. In Quebec about 600 million tons of tailings were piled up in the form of a mountain (Figure 63) which contains about 40% MgO.

Figure 63 - Asbestos tailings in Quebec

Magnola Project

In 1996, a magnesium pilot plant was running at CEZinc in Valleyfield, Quebec to recover magnesium from asbestos tailings containing 24% Mg. In 1997, Noranda Company approved construction of the Magnola magnesium plant at a cost of approximately $730 million to be located in Danville, Quebec next to the tailings disposal heap (Figure 64).

Figure 64 - View of Magnola magnesium plant in Danville, Quebec
Magnola production capacity would be 63,000 tonnes of magnesium per year, or close to 20% of world supply. Plant construction began in 1998 and metal production began in late 2001. The process involved hydrochloric acid leaching, brine purification, drying to produce granular magnesium chloride which are melted and electrolysed to produce metallic magnesium. The metallic magnesium is tapped and then cast in ingots.

Chlorine produced during electrolysis is converted into acid to be used in the leaching stage. It is washed with water and compressed. Then HCl gas is synthesized by burning chlorine with hydrogen. The gas is stripped and distilled so that 99%-HCl gas can be fed into the chlorinator. The hydrochloric acid coming off the chlorinator undergoes a thermal quench and oxidization. It then passes through activated carbon to absorb any chlorinated hydrocarbons that are present. The clean, 35% HCl acid is used in the leach and neutralization circuit.

In January 2003 the plant was shut down for economic reasons. The cost of filtration of the brine was a major cost item because the large volumes of residue to be filtered while other processes using magnesite the residue to be filtered is insignificant. If the process were developed to solve an environmental problem then the amount of tailings consumed annually would be insignificant as compared to the hundreds of millions of tonnes already accumulated.

**Tioxide Canada**

Tioxide Canada in Tracy next door to QIT Fer et Titan in Sorel, Quebec where ilmenite (Figure 65) was treated in electric furnaces to produce iron and Sorelslag (Figure 66). The company treated Sorelslag produced by QIT by concentrated sulfuric acid to produces pure titanium dioxide which is a white pigment (Figure 67). The process produced dilute sulfuric acid which was uneconomical to concentrate and recycle in the process. As a result the dilute acid was thrown in the Saint Lawrence River for many years. When the Province of Quebec formed the Ministry of Environment in the 1960 it warned the industry from throwing the acid in the river. As a result the industry was shut down in the 1980s.

![Figure 65- Museum sample of ilmenite, FeTiO₃ (59.4 % TiO₂)](image)

![Figure 66- Ground titanium slag, FeTi₁₀O₄₁₀ (70-80 % TiO₂)](image)

The solution to this problem was to treat the Sorelslag by hydrochloric acid so that dilute HCl can be economically concentrated and recycled. Incidentally, a process was developed in Canada to treat ilmenite concentrate by concentrated HCl at 80°C to get synthetic rutile (Figure 68) which can be converted to white pigment by thermal methods thus bypassing the electric furnace.

![Figure 67 - Titanium white, ~ 100% TiO₂](image)

![Figure 68- Synthetic rutile, 98% TiO₂](image)

**NORANDA**

Noranda closed in 2002 its copper smelter in Murdochville, Quebec because the ore deposit exploited since 1950s was depleted. It also closed in 2002 its Technology Center near Montreal created in 1970 (Figure 69). It abandoned its process for the recovery of copper in one reactor (Figure 70) because of rapid deterioration of...
refractories.

Figure 69- Noranda Technology Center

Copper refinery

Noranda has a copper refinery in Montreal East (Figure 71) the largest in the world. It also produces copper sulfate for agricultural purposes (Figure 72).

Figure 71- Canadian Copper Refinery in Montreal East - - the largest in the world

Anodic slimes

Anodic slimes remaining in the cells after copper electrefining are treated to recover gold, silver, selenium, and tellurium beside pure copper. Baking with sulfuric acid was used for a long time, e.g.

\[
\begin{align*}
\text{Cu}_2\text{Se} + 4\text{H}_2\text{SO}_4 & \rightarrow 2\text{CuSO}_4 + \text{Se} + 4\text{H}_2\text{O} + 2\text{SO}_2 \\
\text{Cu}_2\text{Te} + 4\text{H}_2\text{SO}_4 & \rightarrow 2\text{CuSO}_4 + \text{Te} + 4\text{H}_2\text{O} + 2\text{SO}_2 
\end{align*}
\]

The problem with this process is the formation of \(\text{SO}_2\). Pressure leaching at 125°C was then used in which selenium was volatilized and recovered while tellurium was recovered from solution:

\[
\begin{align*}
\text{Cu}_2\text{Se} + 4\text{H}^+ + \text{O}_2 & \rightarrow 2\text{Cu}^{2+} + \text{Se} + 2\text{H}_2\text{O} \\
\text{Cu}_2\text{Te} + 2\text{H}^+ + 5/2 \text{O}_2 & \rightarrow 2\text{Cu}^{2+} + \text{TeO}_4^{2-} + \text{H}_2\text{O}
\end{align*}
\]

Further development led to the use of oxidation of anodic slimes in top-blown rotary converter to get directly doré metal. Gases evolved during this treatment are collected for selenium and tellurium recovery.

Cominco

World War I

Consolidated Mining & Smelting Company in Trail, British Columbia together with Anaconda in USA introduced during World War I the leaching – electro winning process for zinc to replace the retort process which was uneconomical (Figure 73). Incidentally, the process was replaced in the 1980s by the pressure leaching process referred to earlier.

Figure 73- The retort process [left] was replaced by the hydrometallurgical process [right] during World War 1
World War II

In World War II 6 tonnes/year electrolytic heavy water plant started operation in 1943 (Figure 74). Heavy water constitutes only one part in 4,500 in ordinary water. The production of heavy water by electrolysis is based on the fact that H$_2$O breaks apart more readily than D$_2$O, and the residual water left after electrolysis is relatively rich in D$_2$O. By reprocessing the residual water over and over again, it was possible to eventually isolate heavy water. This was Canada’s contribution to Manhattan project for the fabrication of an atomic bomb in USA. Heavy water is used in nuclear reactors as a moderator to slow down neutrons.

Figure 74 - Plan for heavy water production at Trail

QSL versus Kivset

The company in 1966 became known as Cominco. It used QSL reactor for few years to produce lead (Figure 75). However, the engineers were unable to operate the American plant and as a result they scrapped it and used the Russian technology known as Kivset (Figure 76).

Figure 75- QSL-lead plant

Conclusions

Canada is a top producer of minerals and metals. Many new technologies and new processes in extractive metallurgy were invented in Canada together with theories of metal extraction were formulated. While some processes proved to be a success others were shut down for being non economical [13].

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