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Pressure Hydrometallurgy Update

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HIDROMETALURGIA A PRESIÓN. UNA ACTUALIZACIÓN

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Resumen
Se destaca una nueva era en la hidrometalurgia a presión cuando el proceso de tostación, lixiviación y electro obtención en la industria del zinc fue reemplazado en la década de 1980 por la lixiviación a presión directa de concentrado de sulfuro de zinc. Desde ese entonces, la lixiviación a presión ha sido reconocida como la tecnología del futuro. Se han venido fabricando e instalando autoclaves de gran tamaño no antes vistos en diversas plantas metalúrgicas para la recuperación de cobre y níquel desde sus concentrados o bien para la liberación de oro de minerales refractarios. Asimismo, se viene trabajando en la recuperación de alúmina de la arcilla por medio de la tecnología a presión. Los autoclaves revestidos con ladrillos resistentes al ácido o con revestimientos de titanio, que, si bien pueden pesar hasta más de 800 toneladas, se vienen trasladando satisfactoriamente desde el taller de fabricación hasta el sitio de la mina por largas distancias.

PRESSURE HYDROMETALLURGY. AN UPDATE

Abstract
A new era in pressure hydrometallurgy is marked when the roasting - leaching - electrowinning process in the zinc industry was replaced in the 1980s by direct pressure leaching of zinc sulfide concentrate. Since then, pressure leaching has received recognition as the technology of the future. Large autoclaves of unprecedented size have been manufactured and installed in a number of metallurgical plants for recovering copper and nickel from their concentrates or liberating gold from refractory ores. An attempt to recover alumina from clay using pressure technology is underway. Autoclaves lined with acid resisting bricks or with titanium clad may weigh as much as 800 tonnes are transported successfully from the manufacturing workshop to the mine site over long distances.
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Presssure hydrometallurgy more than hundred years old. It is applied for leaching of ores or concentrates and for the precipitation of metals or oxides from leach solutions [Figure 1]. Pressure hydrometallurgy expanded gradually resulting in introducing new processes. Equipment used has undergone tremendous changes. The first autoclave used by Bayer in 1892 was a horizontal reactor 1 m diameter and about 2 m long. Today reactors 7 m diameter and 40 m long are used. They are also of variable design, for example, the vertical, the spherical, and the rotating. Tube autoclaves were invented in the 1950s simultaneously at the Aluminum Plant in Sered (Ziar nad Hronom), 50 km east of Bratislava in Czechoslovakia (now the Slovak Republic) and at the Aluminiumwerke in Germany. They are now used on commercial scale in Germany, in Iran, and in Saudi Arabia.
A typical pressure leaching operation is shown in Figure 2. The central equipment in the plant is the autoclave. Other equipment include the high pressure membrane pump to force the slurry in the autoclave and the flash tank to decrease pressure of the exit slurry, to recover its heat in the preheating exchanger of the incoming slurry and to make the hot slurry suitable for filtration.

**HYDROTHERMAL OXIDATION**

Early publications in the 1970s have pointed out to the great potential of pressure hydrometallurgy. Pressure leaching was practiced in the aluminum industry as early as 1889 and application to other industries gradually progressed. Sherritt Gordon Mines in Canada in 1950s were the first to apply the technology on commercial scale for leaching sulfides and adopting precipitation of metals by hydrogen under pressure. In the 1960 pressure technology was applied to ilmenite to produce synthetic rutile. A new era, however, started in the 1980s when pressure leaching of zinc sulfide concentrate was introduced to replace the roasting - leaching - electrowinning process. In the past decade this technology has made significant progress in recovering copper and nickel from their ores or concentrates and liberating gold from its refractory ores. Hydrothermal oxidation of sulfide concentrates has the enormous advantage of producing elemental sulfur, hence solving the SO₂ and sulfuric acid problems associated with smelters [Figure 3].

![Production of elemental sulfur during the aqueous oxidation of sulfides](image_url)
FURTHER WORK

In the 1940's, the need for uranium to make an atomic bomb introduced many new technologies in extractive metallurgy. Among these was the hydrothermal leaching of certain Canadian uranium ores with sodium carbonate solution:

\[
\begin{align*}
\text{UO}_2 & \rightarrow \text{UO}_2^{2+} + 2e^- \\
\text{UO}_2^{2+} + 3\text{CO}_3^{2-} & \rightarrow [\text{UO}_2(\text{CO}_3)_3]^{4-} \\
\frac{1}{2}\text{O}_2 + \text{H}_2\text{O} + 2e^- & \rightarrow 2\text{OH}^- 
\end{align*}
\]

In 1946, the Chemical Construction Corporation in New York City had some problems in the removal of carbon monoxide impurity from synthesis gas, a mixture of hydrogen and nitrogen for ammonia synthesis. This problem was given to Felix A. Schaufelberger (1921-2009), a young graduate from the Federal Institute of Technology in Zurich, Switzerland who had joined Stamford Research Laboratories in Connecticut a year before. Towards the end of 1948, Schaufelberger succeeded in precipitating pure copper from sulfate solution by reduction with hydrogen in quantitative yield. He had also prepared the first samples of nickel and cobalt metal powder. It was also during this period that a new look at the old work was considered by Canadian metallurgist Frank A. Forward (1902-1972) at the University of British Columbia in Vancouver for leaching a nickel-copper ore. In 1956, Sherritt used Forward's ammonia leaching combined with Schaufelberger's work to precipitate nickel from the solution obtained:

\[
\text{NiS} + 2\text{O}_2 + 2\text{NH}_3 \rightarrow [\text{Ni(NH}_3)_2]^2+ + \text{SO}_4^{2-} \\
[\text{Ni(NH}_3)_2]^2+ + \text{H}_2 \rightarrow \text{Ni} + 2\text{NH}_4^+ 
\]

A by-product of this process was ammonium sulfate which was marketed as fertilizer. The process has been successfully in operation by Sherritt Gordon since then using large number of autoclaves and now used worldwide.

RECENT ADVANCES

Zinc

A new era in pressure hydrometallurgy is marked when the roasting - leaching - electrowinning process in the zinc industry was replaced in the 1980s by direct pressure leaching of zinc sulfide concentrate (Figure 4):

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

Since then, pressure leaching has received recognition as the technology of the future. Large autoclaves of unprecedented size have been manufactured and installed in a number of metallurgical plants for recovering copper and nickel from their concentrates or liberating gold from refractory ores. An attempt to recover alumina from clay using pressure technology is underway. Autoclaves lined with acid resisting bricks or with titanium clad may weigh as much as 800 tonnes are transported successfully from the manufacturing workshop to the mine site over long distances.
Titanium

The major titanium mineral is ilmenite, FeTiO₃. In the early method of TiO₂ pigment manufacture the ore was treated with concentrated H₂SO₄ at 110 - 120°C to form ferrous sulfate and titatyl sulfate. After removing the insoluble residue and the crystallization of FeSO₄.7H₂O, titanium oxide is then precipitated from solution by dilution and seeding resulting in the formation of dilute H₂SO₄ for disposal. Because of the pollution problems associated with the disposal of ferrous sulfate and dilute sulfuric acid, iron in the ore was separated at an early stage by an electric furnace process where iron oxide was reduced to metal while titanium was separated as a slag:

\[ \text{FeTiO}_3 + C \rightarrow \text{Fe} + \text{CO} + \text{TiO}_2 \text{(slag)} \]
\[ \text{Fe}_2\text{O}_3 + 3\text{C} \rightarrow 2\text{Fe} + 3\text{CO} \]

The slag is mainly iron magnesium titanate, (Fe,Mg)Ti₄O₁₀, and a small amount of silicates. It is high in titanium and therefore preferable to ilmenite in manufacturing pigment or metal. The sulfuric acid treatment process of the slag, however, still suffered from the disposal problem of the waste acid. As a result a new technology was introduced in the 1960s which involved leaching of ilmenite in autoclaves by 20% HCl at 120°C and 200 kPa and obtaining a residue rich in titanium (90-95% TiO₂) known as "synthetic rutile" (Figure 5):

\[ \text{FeTiO}_3 + 2\text{H}^+ \rightarrow \text{TiO}_2 \text{[impure]} + \text{Fe}^{2+} + \text{H}_2\text{O} \]
The synthetic rutile is then treated by chlorine to prepare TiCl₄ from which TiO₂ or titanium metal are obtained while ferrous chloride is treated by oxyhydrolysis to obtain iron oxide and HCl for recycle:

\[ 2\text{FeCl}_2 + 2\text{H}_2\text{O} + \frac{1}{2}\text{O}_2 \rightarrow \text{Fe}_2\text{O}_3 + 4\text{HCl} \]

**Copper**

In 2004 Phelps Dodge [now Freeport McMoRan] built a plant for pressure leaching of chalcopyrite concentrate at 200°C to get copper in solution and generate sulfuric acid for heap leaching - solvent extraction of oxide operations at Bagdad, Arizona (Figures 6 and 7). Few years later another plant operating at 150°C was constructed to recover elemental sulfur (Figures 8 and 9).

![Figure 6 - Pressure oxidation of chalcopyrite at Bagdad, Arizona](image)

Figure 6 - Pressure oxidation of chalcopyrite at Bagdad, Arizona

![Figure 7 - Recovery of copper from sulfide concentrate](image)

Figure 7 - Recovery of copper from sulfide concentrate
Nickel

Although pressure leaching has been applied for laterites in Cuba since the 1940s and for sulfide concentrates at Fort Saskatchewan in the 1950s, today new plants are much larger and sophisticated than the earlier plants. Also, acid pressure leaching is being applied for the first time to sulfide concentrates.

Papua New Guinea

The $1.5 billion Ramu laterite plant is owned by Highlands Pacific and located in the Papua New Guinea 75 km south west of the provincial capital of Madang uses technology similar to Moa plant in Cuba (Figures 10 and 11). Production is 31,150 tonnes of nickel and 3,300 tonnes of cobalt annually over a 20-year mine life. The ore slurry is readily thickened to produce an autoclave feed containing 32% by weight of solids. A typical autoclave feed grade is 1.2% nickel, 0.08% cobalt, 2.6% Mg, and 3.4% Al. Three autoclaves are in use operating at 250°C. An acid addition rate of 0.27 tonnes of acid per tonne of dry ore results in 96% nickel and cobalt extraction in 60 minutes of leaching. The nickel
and cobalt are then precipitated by NaOH as hydroxides. The hydroxide product is exported for refining.

![Figure 10 - Ramu plant](image)

The upgraded ore is pumped, as a slurry, through a 134 km pipeline to a high pressure acid leach processing facility at Basamuk Bay on the Rai Coast. A sulfuric acid plant producing 3,350 tonnes per day of 98.5% acid supplies the acid requirements. Pilot tests were conducted at Hazen Research in USA and Lakefield Research Laboratories in Canada.

**Madagascar**

Another laterite deposit is being exploited in Madagascar using high pressure acid leaching technology similar to Moa plant in Cuba. At the mine site, an ore preparation plant, a pressure acid leach plant and refinery, and port facilities on the coast were constructed. The ore is transferred to the coast through a 220 km slurry pipeline. The project known as Ambatovy (Figures 12 and 13) is owned by Dynatec, Sumitomo, and SNC Lavalin. Annual design capacity is 60,000 tonnes of high-grade nickel, 5,600 tonnes of high grade cobalt, and 210,000 tonnes ammonium sulfate for at least 27 years. Project investment is estimated at $4.5 billion.

![Figure 11 - One of the three large autoclaves being transported from China to Madang](image)
Figure 12 - Autoclaves at Ambatovy

Figure 13 - Production of nickel, cobalt, and ammonium sulfate fertilizer from laterites in Madagascar
The pressure acid leach of laterite ore takes place in 5 parallel units each consisting of a feed tank, slurry heaters, two Geho PD pumps, an autoclave and flash vessels. The ore slurry received from the thickeners is heated with steam in a series of direct heaters and pumped, continuously, at a temperature of up to 200°C into the autoclaves where it reacts with sulfuric acid and oxygen at 260°C. The operation is similar to Moa plant in Cuba with the exception that the autoclaves are horizontal instead of vertical. Three autoclave are 40 m long and 7 m diameter, divided into seven compartments, made of titanium clad steel and weighs 700 tonnes while the other two are smaller, composed of only four compartments. Three autoclaves were manufactured in China and two in Belgium.

Hydrogen sulfide is used to precipitate nickel and cobalt from the leach solution. The precipitate is then leached by ammonia using Sherritt - Gordon technology of Fort Saskatchewan in Canada to get a solution from which nickel and cobalt are separated by solvent extraction. Pure nickel and pure cobalt are then recovered by precipitation with hydrogen under pressure and ammonium sulfate crystallized from the remaining solution to be marketed as fertilizer.

Canada
With the recent discovery of the Voisey Bay sulfide deposits in the Canadian North it was decided in 2005 to use a pressure leaching process similar to that used for zinc and copper sulfides to produce elemental sulfur instead of SO₂ (Figure 14). 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. The sulfide concentrate is mainly pendlandite - pyrrhotite. The mine is estimated to contain 141 million tonnes at 1.6% nickel. Voisey's Bay is a surface nickel-copper-cobalt mine located in northern Labrador, 37 km southwest of the town of Nain. The mine is operated by Vale Inco.
Gold
The concept of pressure oxidation for treatment of refractory gold ore was tested by the Chemical Construction Corporation in USA and Sherritt Gordon Mines in Canada in the 1950s. The process was developed further by Sherritt in the 1980s, in collaboration with Homestake Mining Company (now Barrick Gold Corporation) for application at the McLaughlin project in California. This was followed by numerous pilot plant studies at Sherritt's facilities in Fort Saskatchewan, Alberta. This led to successful commercialization at numerous gold operations in Canada, Brazil, and Papua New Guinea. At least six new large scale plants for the recovery of gold from refractory ores using high pressure technology went into operation recently in Finland, Russia, Dominican Republic, Brazil, USA, and Papua New Guinea. The Chinese are also considering applying this technology. In addition, there is interest to use chloride medium and oxygen at high temperature and pressure to solubilize gold as chloride complex thus bypassing cyanidation.

Brazil
AngloGold Ashanti Brasil (AGA Brasil) has commissioned in 2012 a refractory gold pressure oxidation plant at the site of the original São Bento operation in Mina Gerais, Brazil which was operated between 1986 and 2007. When the ore body was exhausted AGA Brasil purchased the facility from Eldorado Gold, to process refractory gold concentrates produced from the nearby Corrego do Sítio mining area. The original autoclaves were limited to a maximum operating temperature of 190°C and a pressure of 1700 kPa but were of sufficient size to allow extended pressure oxidation retention times for treatment of the new concentrate (Figure 15). Antimony and arsenic were precipitated to near completion in the first stage of neutralization to a pH of 3 to 5.

Figure 15 - Pressure leaching plant at AngloGold Ashanti Brazil

Dominican Republic
The $3.8 billion Pueblo Viejo mine owned by Barrick Gold and Goldcorp holds 25 million ounces of proven and probable reserves. There are four autoclaves each is 6 m diameter and 40 m long and processes approximately 6000 tonne ore/day liberating about one million ounces of gold per year (Figure 16). The autoclaves operate at 230°C and 3450 kPa and residence 60 to 75 minutes. The autoclaves are the world's largest brick-lined autoclaves.
Tailings from the Pueblo Viejo mine derived from operations between 1992 and 1999 and stock piled at Las Lagunas are about 5 million tons grading 3.8 g/t gold and 38.6 g/t silver. They are being re-processed through flotation, followed by sulfide oxidation using the Albion process prior to extraction of gold and silver utilizing standard carbon-in-leach cyanidation. The Albion process involves fine grinding then leaching at atmospheric pressure. PanTerra Gold anticipates annual production of 69,000 oz Au and 630,000 oz Ag. The first gold was produced in 2012.

**Finland**
The Kittila gold mine is located 900 km to the north of Helsinki at the Suurikuusikko gold deposit. The mine is one of the largest gold-producing mines in Europe. Its commercial production began in May 2009. It is operated by Agnico-Eagle Mines and is expected to produce an average of 173,000 oz of gold a year and has an estimated lifespan of 15 years. The mine contains an estimated 4 million oz of proven gold reserves. The reserves consist of 26 million tonnes of ore with a grade of 4.8g of gold per ton. The majority of the gold is found in arsenopyrite and pyrite and a small fraction in the outer oxidized portions of the minerals. The ore from Kittila is processed through flotation, pressure oxidation, and carbon-in-leach circuits, and electrowinning (Figure 17).
Russia
By the end of 2013, Polymetal International will start treating its refractory gold ores at the Pokrovka mine [Malomir and Pioneer deposits] in the Russian Far East by pressure oxidation process. The concentrate, ground to 90% -44 pm, in the form of a pulp is fed to the acid treatment facilities, where carbonates are decomposed. The acidic pulp is pumped into a three-stage counter-current washer to decrease the chloride concentration to a minimum. The thickened product is then fed into the autoclave using a high-pressure pump.

Pressure oxidation is carried out in a horizontal autoclave at 225-230°C and an oxygen pressure of 0.5-0.7 Mpa, with the total pressure in the autoclave at 3.2-3.5 MPa. The autoclave is divided into four sections, the first of which is twice the size of the others. The autoclave also has five impellers, of which two are located in the first section. Oxygen is supplied from the underside of each impeller and cooling water is supplied to each section independently. The oxidation of pyrite and arsenopyrite are exothermic, and enables the process to run auto-thermally. Any excessive heat is controlled by feeding cold water into the autoclave. Oxidized pulp from the last section of the autoclave is discharged into two flash tanks connected in a series. The pressure in the first tank is 0.7 MPa, with the pulp temperature at 170°C, with the second unit at atmospheric pressure with a pulp temperature of —100°C. The pulp is thickened and filtered then the cake is washed and delivered for cyanidation. The acidic autoclave solution is then neutralized, first with limestone to a pH of 4.5, and then with lime, to a pH of 9-10, before it is pumped to the tailings facility.

The key factor affecting the gold recovery from the carbon-bearing Malomir concentrate was the presence of chloride ions in the process water. In 2011, a pilot pressure oxidation unit was installed at the Petropavlovsk pilot plant in Blagoveschensk. To process the flotation concentrates from both the Pioneer and Malomir deposits, it was decided to build a centralized pressure-oxidation unit at the Pokrovskiy mine, 670 km from Malomir and 40 km from Pioneer. The location was chosen for its existing supporting infrastructure, including a resin-in-pulp process plant.

Outotec in Finland will manage the design and construction of the pressure oxidation plant in collaboration with Gidrometallurgiya R&D Centre in Saint Petersburg. It will supply 6 horizontal autoclaves each of 3m diameter and 1 5m long, a total capacity of 90 m³ and an operational capacity of 50 m³. The acid-proof brick lining will be produced and inserted by DSB in Germany.

USA
Newmont Mining Corporation started mining gold at Carlin, Nevada in 1965. In 2001, it acquired Battle Mountain Gold and in 2002 Normandy Mining in Nevada. Most operations are located on the Carlin Trend west of Elko. The Twin Creeks and Lone Tree Complex are in the Winnemucca region further west. The Phoenix gold - copper project near Battle Mountain produces about 420,000 oz/y of gold and 21,000 t/y of copper.

High-grade oxide and sulfide ore is treated by milling and cyanidation, but for the lower-grade oxides heap-leaching is used. For the refractory ores the company completed in 1994 a roasting unit for higher grades and a bio-oxidation system for lower grades. Refractory ore with a carbonaceous content is treated in the bio facility or by ammonium thiosulfate leaching. The Winnemucca operations use
autoclaves to pre-treat refractory ores. In 2005, open pits mined 175 million tonnes of material and the underground mines 1.42 million tonnes. The oxide mills processed 4.20 Mt averaging 4.3g/t gold, the refractory mills 8.15 million tonnes averaging 6.8g/t, and leach dumps 17.5 million tonnes averaging 0.9g/t to give a total output of 2.46 million oz of gold. Barrick Gold already has a pressure leaching plant in Elko, Nevada for liberating gold in pyrite followed by cyanidation (Figure 18).

![Figure 18 - Barrick Gold pressure leaching plant for liberating gold in pyrite at Elko, Nevada](image)

**New Zealand**

The Macraes Goldfield is New Zealand's largest gold producing operation, consisting of the Macraes Open Pit and Frasers Underground mine. The Macraes mine has been in operation since 1990 and produces about 130 000 oz/annum. Macraes is located 100 km north of Dunedin in the Otago region of the South Island of New Zealand. The Frasers Underground was commissioned in 2008. The processing plant is situated within short distance of the Macraes Open Pit and includes a pressure oxidation plant for the processing of sulfide ore, carbon in leach, and electrowinning (Figure 19). Refractory concentrate from the Reefton processing plant is transported by road and rail to Macraes.
The Reefton mine was commissioned in 2007. A gold bearing concentrate is produced at the mine which is then railed over 600 km south to Palmerston from where it is trucked to the Macraes operation for processing. Reefton produced 85,843 ounces of gold in 2010.

**Status**
Pressure oxidation of refractory gold ores started in 1985 and since then many plants were constructed (Table 1).

*Pressure leaching of refractory gold ore in chloride medium*
It was found some time ago that it was possible to leach gold from a refractory sulfide ore at high temperature and oxygen pressure to form a gold chloride complex from which metallic gold can be precipitated by a variety of reducing agents thus bypassing cyanidation. The concept was developed further as the Platsol process.
## Table 1: Status of treating refractory gold ores by pressure hydrometallurgy

<table>
<thead>
<tr>
<th>Start up</th>
<th>Plant Location</th>
<th>Owner</th>
<th>Feed</th>
<th>Capacity t/d</th>
<th>Number of autoclaves</th>
</tr>
</thead>
<tbody>
<tr>
<td>1985</td>
<td>McLaughlin USA</td>
<td>Homestake USA</td>
<td>ore</td>
<td>2700</td>
<td>3</td>
</tr>
<tr>
<td>1986</td>
<td>San Bento Brazil</td>
<td>Genmin S. Africa *</td>
<td>concentrate</td>
<td>240</td>
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<tr>
<td>1988</td>
<td>Mercur, Utah USA</td>
<td>American Barrick Canada</td>
<td>ore</td>
<td>680</td>
<td>1</td>
</tr>
<tr>
<td>1989</td>
<td>Getchell USA</td>
<td>First Miss Gold</td>
<td>ore</td>
<td>2730</td>
<td>3</td>
</tr>
<tr>
<td>1990</td>
<td>Goldstrike Nevada, USA</td>
<td>American Barrick Canada</td>
<td>ore</td>
<td>1360</td>
<td>1</td>
</tr>
<tr>
<td>1991</td>
<td>Goldstrike Nevada, USA</td>
<td>American Barrick Canada</td>
<td>ore</td>
<td>5450</td>
<td>3</td>
</tr>
<tr>
<td>1991</td>
<td>Porgera, Papua New Guinea</td>
<td>Placer Dome Canada**</td>
<td>concentrate</td>
<td>1350</td>
<td>3</td>
</tr>
<tr>
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<td>Placer Dome Canada **</td>
<td>concentrate</td>
<td>70</td>
<td>1</td>
</tr>
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<td>1992</td>
<td>Lihir, Papua New Guinea</td>
<td>Neco Minerals</td>
<td>concentrate</td>
<td>90</td>
<td>1</td>
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<td>ore</td>
<td>11580</td>
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</tr>
<tr>
<td>1994</td>
<td>Porgera, Papua New Guinea</td>
<td>Placer Dome Canada **</td>
<td>concentrate</td>
<td>2700</td>
<td>6</td>
</tr>
<tr>
<td>1997</td>
<td>Lihir, Papua New Guinea</td>
<td>Rio Tinto</td>
<td>---</td>
<td>---</td>
<td>3</td>
</tr>
<tr>
<td>1999</td>
<td>Twin Creeks, Nevada, USA</td>
<td>Newmont</td>
<td>concentrate</td>
<td>---</td>
<td>---</td>
</tr>
<tr>
<td>1999</td>
<td>Macraes, New Zealand</td>
<td>Macraes Goldfield</td>
<td>concentrate</td>
<td>---</td>
<td>1</td>
</tr>
<tr>
<td>2006</td>
<td>Madang, Papua New Guinea</td>
<td>Highlands Pacific</td>
<td>concentrate</td>
<td>---</td>
<td>---</td>
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<tr>
<td>2009</td>
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<td>Agnico-Eagle</td>
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<tr>
<td>2009</td>
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<td>Barrick</td>
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<td>6000</td>
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<tr>
<td>2012</td>
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<td>Polymetal International</td>
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<td>---</td>
<td>6</td>
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<tr>
<td>2012</td>
<td>São Bento Brazil</td>
<td>AngloGold Ashanti Brasil</td>
<td>concentrate</td>
<td>---</td>
<td>---</td>
</tr>
</tbody>
</table>

*Closed in 2007 because of exhaustion of ore body. ** Now Barrick

### Alumina from clay

Alumina required for aluminum production is presently recovered from bauxite. Russia is the only country that has an operation based on non-bauxitic raw material. Industrialized countries lacking bauxite deposits are obliged to import it although they have abundant clay and other aluminum silicate raw materials. Therefore, there has been extensive research over the years to recover alumina from domestic sources, but all processes developed so far were uneconomical. It has been generally known that acids are effective in extracting aluminum from clay at room temperature only if the clay was first dehydroxylated at 400°C. For example, to render kaolinite, the main clay mineral, attacked by dilute acids, it must be heated at 400-800°C to convert it to metakaolin:

\[
\text{Al}_2\text{(Si}_2\text{O}_5\text{)}(\text{OH})_4 \rightarrow \text{Al}_2\text{O}_3 \cdot 2\text{SiO}_2 + 2\text{H}_2\text{O}
\]

Metakaolin which is an amorphous aluminum silicate can be leached with acid to extract aluminum selectively leaving behind crystalline SiO₂:
\[
\text{Al}_2\text{O}_3.2\text{SiO}_2 + 6\text{H}^+ \rightarrow 2\text{Al}^{3+} + 2\text{SiO}_2 + 3\text{H}_2\text{O}
\]

All attempts to apply this technology cannot compete with Bayer process. The problem with Bayer process, however, is the generation of a large amount of red mud which creates disposal problem. For each ton of alumina produced one ton of red mud is generated. All this may change in the future. Researchers at the former US Bureau of Mines extracted alumina from un-calcined kaolinitic clay in 15 minutes by heating at 200 °C using 20-27% HCl at 20% excess to the stoichiometric amount [9]:

The process is being developed further by Orbite Aluminae in Quebec Province in Canada and an industrial plant is planned. An advantage of the new technology is that silica is produced which can be considered as a byproduct while red mud from bauxite is a waste product. In this process, aluminum chloride is crystallized from solution by sparging with HCl gas. The crystals are separated and decomposed to Al₂O₃ while the mother liquor is decomposed at high temperature to recover Fe₂O₃ and HCl (Figure 20).

The process however cannot compete with alumina from bauxite because of the low tenor of the clay, the difficulty of obtaining alumina from an acid solution as compared with the ease of precipitating aluminum hydroxide from an alkaline solution. That is why the process was shut down after 5 years operation and spending $ 127 million.

**TRANSPORTATION OF AUTOCLAVES**

Most autoclaves have to be transported from manufacturing workshop to the mining site. This is a major engineering challenge but it is done. For example, the autoclaves for Madagascar were transported from Shanghai but those for the Dominican Republic were transported from Kuantan in Malaysia to Port of Samana. Each autoclave, weighing 750 tonnes, was lifted aboard the cargo ship for a four-week journey across the Pacific through the Panama Canal to the Port of Samana. From there, the 120 km, 18-day trip to the mine site required thorough surveying and temporary modifications to infrastructure including bridges, roads, traffic signs and overhead obstructions. In the end, 27 bridges were reinforced with portable ramps or bypassed by temporary bridges.

Each autoclave was unloaded from the ship onto a pair of heavy-haul trailers, each with 22 sets of axles and 12 tires per row, and a 400-tonnes-capacity turntable to allow trailer rotation under each end of the autoclave (Figure 21). Upon reaching the Pueblo Viejo mine, each autoclave was transferred to a self-propelled mobile trailer that was configured to comply with ground pressure limits and manoeuvrability constraints. Supported by auxiliary trucks for additional pulling, pushing, and braking capacity, the mobile trailer was able to manoeuvre the vessels close to their finals site.
LABORATORY AUTOCLAVES AND PILOT PLANTS

Laboratory autoclaves for hydrometallurgical investigations are available in a variety of sizes, models, and materials of constructions. They vary in sizes from 25 mL to 2 L for laboratory studies and 5 to 50 gallons for pilot plant work. They are essential tools for studying aqueous oxidation of sulfide concentrates, dissolution of oxide minerals at high temperature and pressure and hydrothermal precipitation reactions. The maximum pressure and temperature at which any reactor or pressure vessel can be used will depend upon the design of the vessel and the materials used in its construction. Since all materials lose strength at elevated temperatures, any pressure rating must be stated in terms of the temperature at which it applies. A review of existing models and their accessories are available. Pilot plant units for pressure oxidation studies are now available on the market (Figure 22). This will certainly facilitate research in this area.
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