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## **Competitive and Strategic Considerations for the Extraction of High Value Non-Commodity Metals: An Overview of Lithium, Magnesium and Rare Earths Production**

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### **ABSTRACT**

High value but non-commodity metals such as lithium, magnesium and the rare earths have unique considerations for the development of new mines and the selection of extraction technologies. Approximately 60% of the world's lithium is extracted in South America by three principal producers, whereas over 90% of magnesium and rare earth metals are produced in China. With production of these metals concentrated in a few hands or to a certain geopolitical region, the feasibility of new projects is largely contingent on the ability to competitively produce these metals relative to existing producers and develop strategic and robust market forecasting on both demand and price. An overview is presented on the current extraction methods and operating practices at these production sites and what new mining projects outside these control centers must confront to remain feasible.

### **LITHIUM PRODUCTION**

#### Market and Growth

The common industry metric for quantifying the lithium production and markets is the lithium carbonate equivalence<sup>1</sup> since it is the principal primary product of many lithium operations and the precursor for the preparation of many derivative lithium compounds. Global production is estimated at 180,000 metric tonnes per year of lithium carbonate. Recent interest in lithium and the impetus to develop new mines has been founded on the anticipated growth in sales of hybrid electric vehicles and plug-in electric vehicles

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<sup>1</sup> One tonne of lithium is equivalent to 5.32 tonnes of lithium carbonate

using lithium-based batteries with speculation that market prices for lithium carbonate will escalate.

### Lithium Mining

Over 60% of global lithium carbonate production is controlled by three major lithium corporations – SQM (Sociedad Quimica y Minera), Chemetall (Rockwood Lithium) and FMC. The source materials are continental lithium-bearing brines extracted from ancient salt beds. Most production is attributed to three operations based in South America; both SQM and Chemetall have brine operations at the Salar de Atacama, Chile while FMC operates at the Salar del Hombre Muerto, Argentina; a smaller operation controlled by Chemetall is based at Silver Peak (Clayton Valley), Nevada, USA. The production capacities of the three lithium majors are summarized as follows:

**Table 1 Estimated production capacity of the three major lithium producers from brines**

	Brine Source	Location	Year Production Established	Current LCE Production Capacity (tpy)
SQM	Salar de Atacama	Chile	1997	60,000
Chemetall	Salar de Atacama	Chile	1984	30,000
	Clayton Valley	USA	1966	4,500
FMC	Salar del Hombre Muerto	Argentina	1997	20,000

Other brine-based operations are found in the Tibetan Plateau in China but are of smaller scale and collectively amount to less than 10,000 tpy of lithium carbonate. New brine projects under development in South America include the Salares of Cauchari and Olaroz, Salinas Grande, and Salar del Rincon with planned lithium carbonate production capacities between 15,000 tpa to 20,000 tpa; there is also renewed interest in the exploitation of the Salar de Uyuni in Bolivia, which is often cited as one of the world's largest lithium resource. Brine resources currently exploited or under development occur in desert environments in elevated plateaus of Chile, Argentina and Bolivia and the Tibetan and Qinghai Plateaus in the People's Republic of China (PRC) where certain geological events isolated saline water bodies that were further concentrated by the prevailing arid climate. The brines currently exploited at Atacama, Chile and Hombre Muerto, Argentina, have exceptionally high lithium concentrations and, unlike brine at Uyuni, Bolivia, they also have relatively low magnesium to lithium ratios ( Table 2) - the former being a problematic and a costly element to remove. The range of lithium concentration in the brines at Atacama is 1,000 – 7,500 ppm, at Hombre

Muerto, 200 – 2,000 ppm, at Silver Peak, 100 – 300 ppm and at Uyuni, 100-700 ppm <sup>[i]</sup>.

**Table 2 Lithium concentration and magnesium to lithium weight ratio of select brines <sup>[i,ii]</sup>.**

Brine Source	Location	Range of Li concentration (ppm)	Mean Li concentration (ppm)	Mean Mg/Li weight ratio
Salar de Atacama	Chile	1,000 – 7,000	1,800	6.2
Salar del Hombre Muerto	Argentina	200 – 2,000	620	1.4
Clayton Valley	USA	100 – 300	110-120	1.4
Salar de Uyuni	Bolivia	100 – 700	425	18.6

Prior to the development of South American brine resources, lithium was principally mined from hard rock pegmatites containing spodumene, lepidolites and petalites. North Carolina was the former center of spodumene mining in the USA; Cyprus Foote Mineral (later acquired by Chemetall (Rockwood Holdings)) operated at Kings Mountain while Lithium Corporation of America or LithCo (later acquired by FMC) mined the Long Creek area, both adjacent to the North Carolina Cherryville Quartz Monzonite. Head grades at these mines averaged about 1.2 - 1.5% lithium oxide (Li<sub>2</sub>O)<sup>[iii]</sup>. Foote concurrently operated its brine operation in Clayton Valley, Nevada near the city of Silver Peak, which has been in continuous operation since the mid-1960's (now owned by Chemetall) and nominally produces 4,500 tonnes per year of lithium carbonate.

Both Foote and LithCo initiated exploration programs in South America, with the former concentrating activities on Salar de Atacama in Chile and the latter targeting the development of Salar d'Uyuni in Bolivia. FMC (formerly LithCo) abandoned the Bolivian venture despite having reached an agreement with the government ostensibly because local opposition to the project at Uyuni prevented the contract from being executed. Rather, FMC developed the more modest sized Salar del Hombre Muerto in Argentina, which began operating in 1997, although at below design capacity and with intermittent closures up until 2007 due to technical issues and poor market conditions. Foote had established its operation on the southern part of Salar de Atacama and began producing lithium carbonate in 1984. SQM also established brine operations at Salar de Atacama and started production of lithium carbonate as a by product of potash in 1997; once in operation, SQM halved the selling price of lithium carbonate. As a consequence, all spodumene mining in North Carolina ceased and a new 5,000 tpa lithium carbonate plant built by Gwalia (later acquired by Talison) in Australia was mothballed. The latter was built to convert spodumene mined from Greenbushes deposit into lithium carbonate.

Hard rock mining of lithium minerals now accounts for an overall smaller proportion of

the global lithium supply although the output of the Talison mine at Greenbushes, Australia is comparable in scale to SQM at Atacama with respect to the amount of extracted lithium. In 2012, Talison (formerly Gwalia)<sup>2</sup> at Greenbushes, produced 357,000 t of spodumene concentrates<sup>[iv]</sup> (53,000 t of lithium carbonate) or approximately 25-27% of current lithium supply and eclipsing the combined output of smaller established operations in China, Portugal, Zimbabwe and Brazil. Greenbushes ore is exceptionally high grade at 3.2% Li<sub>2</sub>O (pure spodumene contains 8% Li<sub>2</sub>O at its theoretical maximum) that is easily accessible by surface mining and is mined at low strip ratios. Tanco was the sole Canadian supplier of lithium minerals to market until 2009 when it closed its spodumene operation at Bernic Lake, Manitoba. In December 2012, Canada Lithium began commissioning a mine and the new lithium carbonate plant of its Quebec Lithium project near the La Corne township - a site of former spodumene mining and lithium carbonate production between 1955 and 1965 – at an installed capacity of 17,000 tpa. There are a number of other pegmatite resources in Canada that have been targeted for potential development although none have progressed beyond the pilot plant stage.

Talison produces two types of spodumene concentrates: chemical grade (6% Li<sub>2</sub>O) for conversion to lithium carbonate and a low-iron technical grade of various lithium oxide content (5%, 6.5%, 7%, 7.5% Li<sub>2</sub>O) for additives in glass and ceramics<sup>[iv]</sup>. Upwards of 80% of Talison output is chemical grade spodumene concentrate although there is no commercial production of lithium carbonate in Australia. All of Talison's chemical grade concentrate is sold to China for conversion to lithium carbonate and accounts for 70-80% of the Chinese market requirements<sup>3</sup>.

### Lithium Carbonate Production from Spodumene

Various processes have been developed for the conversion of spodumene into lithium carbonate or lithium sulfate. There are two commercially important methods used for lithium carbonate production from spodumene or its ores; the sulfuric acid process and the no longer used alkaline methods. These methods are detailed in technical encyclopaedias<sup>[v,vi]</sup> and elsewhere. The former was previously used by LithCo (FMC) and Cyprus (Chemetall) on spodumene mined from North Carolina which has also been adopted by Canada Lithium for the Quebec Lithium project. Following, mineral dressing, a concentrate of alpha-spodumene is produced. Relatively inert, the alpha-spodumene concentrate must be calcined at about 1100 °C to transform the crystal structure into beta-spodumene, to make it amenable to acid attack. Following

<sup>2</sup> Controlling interest in Talison was bought by China-based Chengdu Tianqi Industry (Group) Co., Ltd. ("Tianqi") on March 26, 2013

<sup>3</sup> Asian Metal Interview with Peter Oliver, Chief Executive Officer and Managing Director of Talison Lithium Limited [http://www.asianmetal.com/metal\\_cron/index\\_lunshi\\_oliver\\_en.shtml](http://www.asianmetal.com/metal_cron/index_lunshi_oliver_en.shtml)

calcination, the concentrate, is cooled, ground and then contacted with sulfuric acid. The mixture is heated in a rotary kiln where reaction with the acid leads to the replacement of lithium by hydrogen in the lithium structure yielding an insoluble residue and soluble lithium sulfate. Leaching of the residue yields an impure lithium sulfate solution, which has to be neutralized, filtered and purified. In the final stages of the process, the purified lithium sulfate solution is concentrated in multi-effect evaporators to produce a concentrated lithium sulfate solution that can then be used to produce lithium sulfate crystals or be reacted with soda ash to precipitate lithium carbonate.

In alkaline methods, the ore was calcined with limestone at high temperature; the resulting clinker is cooled, ground and then water leached to produce a solution of impure lithium hydroxide. By use of the proper additives, solutions of either lithium sulfate or lithium chloride can be made.

### Lithium Carbonate Production from Brines

With the exception of FMC's operation in Argentina, the SQM and Chemetall operations extract lithium by a 'conventional' route using solar evaporation ponds and the phase chemistry characteristics of the brine to yield a final brine bittern concentrated in lithium chloride. This bittern is then transported to a chemical plant for purification and conversion to lithium carbonate. Despite the amenability of the brine at Hombre Muerto to conventional processing, FMC opted to develop a resin/sorbent for selective extraction of lithium from brine following which the resin was washed and the resultant eluate concentrated by solar evaporation. This bittern is similarly converted to lithium carbonate.

In some plant configurations, the bittern from the evaporation ponds is first diluted in preparation for boron recovery by solvent extraction. Following boron removal, residual magnesium in the brine is precipitated as magnesium hydroxide with lime and calcium is subsequently precipitated as calcium carbonate with soda ash. The purified brine is filtered and then heated to about 80-90 °C so that in the final soda ash addition step lithium carbonate is effectively precipitated due to its lower solubility at elevated temperature. The solution is filtered and the lithium carbonate residue washed and dried while the mother liquor is re-circulated into the circuit.

### Lithium Carbonate Production - Competitive and Strategic Considerations

The best brine resources under exploitation for lithium are found in the elevated South American plateaus of the Puna Altiplano and the Atacama Desert. A number of salt pans are found in and around these regions and are the remnants of ancient saline

bodies trapped inland at high elevation that experienced cyclical evaporative cycles. Consequently, the brines residing in the pores of the precipitated salts are enriched in dissolved salts both from the natural evaporation that has taken place as well from the contribution of volcanic activity. The geopolitical or geographical occurrence of these and other brine resources is attributed to the geological events in the South American continent that lead to the formation of these plateaus. The favorable characteristics of the particular deposits under exploitation are the –

- Sizeable lithium reserves/resources
- Favorable climatic conditions for solar concentration of the brine
- High lithium concentration in the brine
- Good hydrological characteristics of the deposit

Other factors in Chile and Argentina favoring the exploitation of these deposits are their:

- Political stability and democratic systems of government
- Mining-friendly orientation
- Low labour costs and experienced workforce
- Developed road and energy infrastructure near the project sites

Following the transition to democratic systems of governance, Chile and Argentina liberalized the mining industries to varying degrees to attract foreign investment. Both countries have skilled workforces with lower labour rates compared to the United States, Canada, and Australia.

No new brine resources identified or under development in Chile and Argentina match the lithium concentration and/or low magnesium to lithium ratio of existing commercial operators. The pond system and brine well-field are the most capital intensive investment of a brine project and are directly impacted by the brine chemistry (lithium concentration) and the hydrological characteristics of the salt flat. Pond system size increases with decreasing initial lithium concentration in the brine since more area is required to achieve the desired concentration factor. The size of the brine well-field and number of installed pumping stations is similarly affected since the volume of brine (and lithium) throughput required to reach production targets increases with decreasing lithium concentration in the brine. If the hydrological characteristics of the salt flat are such that brine extraction requires the installation of many pumping stations then well-field capital investment and operating costs both increase. As such, the cost of lithium production from new operations is likely to be higher than the upper limit of the big three lithium brine producers. Notwithstanding these operational considerations, the elevated concentration of a deleterious element such as magnesium in the brine will also increase operating costs. The latter is an important technical consideration for the development of the Salar de Uyuni, Bolivia where the high lithium concentration in the brine is also accompanied by a high magnesium to lithium ratio.

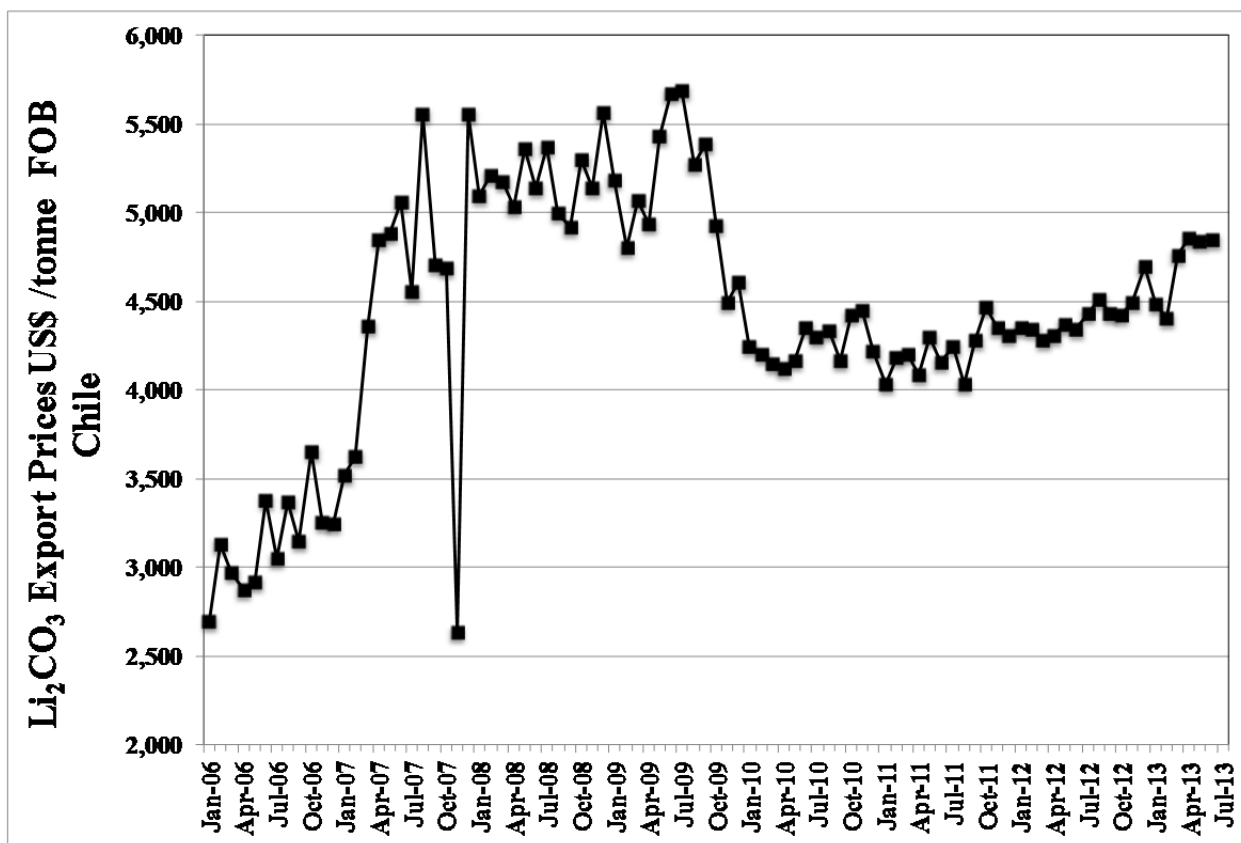
The production of lithium carbonate from open pit hard rock mining and the calcination of the spodumene concentrate are energy-intensive relative to brine-based operations. The latter rely on hydraulic extraction rather than mechanical mining of the deposit while solar evaporation is the principal method of concentration. Also, the conversion of lithium chloride brines to lithium carbonate is carried out at much lower temperatures compared to the acid and alkali processes used for spodumene that require initial calcination of the feed at 1100 °C.

Current brine-based lithium producers do not disclose technical or financial details on the production of lithium carbonate. In 2007, TRU had developed an internal model and comparative index of lithium carbonate production costs from current brine-based producers and hard rock operations at various head grades. It was found that operating costs of the big three lithium carbonate producers from brines were similar and within a narrow cost band of a few hundred dollars that were approximately one-third to one-half the production costs of a hard rock mining operation for head grades of 1-1.5% Li<sub>2</sub>O. In 2009, Credit Suisse<sup>[vii]</sup> estimated lithium carbonate production costs for brine-based projects at \$1,400-\$2,600 per tonne and for hard rock operation at \$4,800 per tonne.

Also in 2007, TRU Group had performed a long-term market outlook for lithium pricing, the results<sup>4</sup> showed sufficient expansive capacity with existing producers to meet future short term demand while allowing for the market to accommodate several new lithium projects already in the pipeline that would mitigate against potential high price fluctuations as lithium demand increased. As a result, TRU concluded that the price of lithium carbonate will remain relatively stable at \$4500 +/-20% for the long term. Despite fluctuations that may have appeared in spot prices for lithium carbonate, export prices from Chile have remained stable and between \$4000 and \$5000 per tonne lithium carbonate over the last few years (Figure 1) and in line with TRU projections made in 2007.

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<sup>4</sup> Summary results presented at Industrial Mineral's Lithium Supply & Markets 2009 conference in Santiago, Chile. Entire presentation can be viewed at <http://trugroup.com/lithium-market-conference.shtml>



**Figure 1 Lithium carbonate export prices in US\$/tonne FOB Chile from January 2006 to June 2013 (Source: Ecomex).**

In the context of developing new lithium projects, production costs must be competitive to current producers. When SQM entered the lithium carbonate market in 1997, prices for lithium carbonate dropped to below \$2,000 per tonne, such that FMC stopped producing lithium carbonate at Hombre Muerto temporarily and sourced its lithium carbonate needs from SQM. Over the next ten years, prices climbed about threefold up until the global economic downturn of 2008, which saw a decline in manufacturing, and a consequent drop in demand for lithium carbonate and the depression of the market price to below \$4,500 per tonne from mid-2009 onwards. Therefore, both competitive production costs relative to current producers must be attained and realistic price assumptions adopted in the financial analysis for assessing the viability of any new brine or hard rock project. In some financial analyses, \$6,000 to \$7,000 per tonne lithium carbonate were adopted for long term price projections. While these may occur as short incident spot prices, TRU Group's opinion is that they are not justifiable.

Notwithstanding these considerations, current producers have the ability to expand production at the current sites from existing reserves and resources and through pricing strategies and control on distribution networks maintain market share to the possible detriment of new projects. Hard rock mining projects with typical ore grades of 1-1.5% Li<sub>2</sub>O would be particularly vulnerable if current brine producers discount lithium



carbonate prices to maintain market share. In North Carolina, the historical grade of the pegmatites mined by Foote and LithCo was 1.5%  $\text{Li}_2\text{O}$  when lithium carbonate production from them was rendered uneconomical in face of new competition from South American brine-based producers. More recently, the Mt Cattlin mine near Ravensthorpe Australia developed by Galaxy Resources was mined at a nominal head grade of 1.1%  $\text{Li}_2\text{O}$ . Meant to provision the company's newly built 17,000 tpa lithium carbonate plant located in Jiangsu Province, China, Galaxy Resources shut the mine after operating it briefly from 2010 to 2012. Presently, Galaxy Resources outsources its feedstock requirements for lithium carbonate production. Quebec Lithium at La Corne, which currently mines ore with a head grade of 0.98%  $\text{Li}_2\text{O}$  to supply its 17,000 tpa lithium carbonate plant may face similar challenges as Galaxy Resources. Talison Greenbushes mines ore grading 3.2%  $\text{Li}_2\text{O}$  and is situated in south-western Australia near port facilities and developed infrastructure; yet despite these evident advantages, the company is only cautiously evaluating the construction of a 20,000 tpa lithium carbonate plant near its mine.

### Summary

1. The current big three lithium carbonate producers from brine are the most cost effective operations due to a number of advantages namely –
  - High lithium concentration and low magnesium to lithium ratio in the brine or
  - Good hydrological (flow) characteristics of the salt flat
  - Large reserves and resources to allow for expanded production
2. The Talison Greenbushes mine has parallel advantages with
  - High grade ore of 3.2%  $\text{Li}_2\text{O}$
  - Near surface/easy access to the ore body
  - Sufficient reserves and resources to expand production of spodumene concentrate
3. New projects face the challenges of being cost competitive to existing producers and acquiring market share; current producers have distribution networks in place that can hinder new producers from reaching potential clients.
4. Elevated prices for lithium carbonate used for assessing the financial viability of new projects is not advisable and are not likely to be sustained in the long term.

## MAGNESIUM METAL PRODUCTION

The commercial technologies used for magnesium smelting can be divided into two classes: thermic and electrolytic, with variants within each class. The history of magnesium production can be summarized as one in which saw numerous openings

and closures of magnesium plants both electrolytic and thermic as a result of demand increases during calamitous wartime events, particularly in World War II, and consequent drop in use of the metal during peacetime. Development of new alloys and applications saw a gradual increase in demand from the post World War II era. Electrolytic processes were the mainstay for magnesium metal production up until the start of 21<sup>st</sup> century when China adopted thermic technology to exploit its dolomite resources and quickly built up capacity to become the dominant global magnesium producer.

### Electrolytic Magnesium Production<sup>[viii,ix,x,xi, xii]</sup>

Electrolytic processes installed in Western Europe, North America and Japan (ca WWII) produced magnesium from anhydrous or partially dehydrated magnesium chloride; US Magnesium at Great Salt Lake, Utah, USA is the only plant producing magnesium from magnesium chloride. Soviet electrolytic technology developed in 1934 uses natural or synthetic carnallite (KCl.MgCl<sub>2</sub>) for magnesium production with plants nominally operating in Russia, Kazhakstan, Ukraine and Israel.

### Magnesium Chloride Electrolysis

The raw material to produce feedstock for electrolysis varies as does the electrolytic technology, which was an evolution of the original IG Farben cells originally developed in Germany during the 1920's. Magnesium chloride has been prepared from seawater, natural brines, magnesite, dolomite as well as asbestos tailings containing magnesium-bearing serpentine minerals. The principal objective in feed preparation is to prepare anhydrous or sufficiently dehydrated magnesium chloride that can be reduced to molten magnesium metal and chlorine gas. Failure to control moisture in the feed can result in excess oxidation of magnesium chloride to magnesium oxy-compounds to the detriment of the process. In most operations, the magnesium oxide feed was limited to less than 0.1%. Of the seven electrolytic plants operated in recent history reviewed below, only US Magnesium's Rowley Plant remains open in 2013.

- **DOW Magnesium, Freeport, Texas, USA** – produced partially dehydrated magnesium chloride from seawater and dolomite. Magnesium hydroxide was precipitated from seawater with calcined dolomite and then converted to hydrated magnesium chloride with hydrochloric acid and then partially dehydrated to MgCl<sub>2</sub>.2H<sub>2</sub>O by spray drying before being fed into the DOW electrolytic cell as a 'wet' feed containing 27% water. The plant operated from 1941 until September 1998 when it sustained heavy damage from multiple lightning strikes and flooding during a major storm event. In face of a changing economic environment and costly damage to the plant, DOW exited the magnesium business. The initial capacity of the plant was 18,000 tpa and had expanded to 65,000 tpa, which

made DOW the largest American producer of magnesium at the time.

- US Magnesium (f. Magcorp), Great Salt Lake, Utah, USA** – Produced magnesium chloride from seawater brine from Great Salt Lake. Solar evaporation of the brine leads to precipitation of potassium chloride, sodium chloride and some magnesium as carnallite. The concentrated brine is then treated with calcium chloride to precipitate gypsum and then subject to solvent extraction to remove boron. The purified brine is heated and then spray dried. The resulting magnesium chloride powder is melted in an electric furnace and treated with carbon and chlorine gas to reduce MgO and water; additional reduction of impurities is achieved with further treatment by chlorine gas and carbon in a subsequent reactor. In current operations, the molten magnesium chloride is then fed into diaphragmless Alcan monopolar cells. Magnesium production began in 1972 when owned by National Lead but experienced operating difficulties forcing a closure of the plant in 1975 until they were resolved with assistance of Norsk; the operation was then sold to AMAX Inc in 1980 and was then sold to Renco Inc in 1989 which renamed the operation Magnesium Corporation of America (Magcorp). In 2001, Magcorp filed for bankruptcy; in 2002 Renco repurchased the assets and formed US Magnesium. The company expanded capacity in 2012 to 63,500 tpa from 42,000 tpa. It is the only magnesium production facility in North America.
- Norsk Hydro, Porsgrunn (Haraya), Finland** – produced magnesium chloride brine from two sources: seawater and by dolomite leaching with hydrochloric acid. The resulting brine was then subject to evaporation to produce molten bischofite ( $\text{MgCl}_2 \cdot 6\text{H}_2\text{O}$ ). This solution was sent to a prilling tower to produce granules (prills) of partially dehydrated magnesium chloride ( $\text{MgCl}_2 \cdot 2\text{H}_2\text{O}$ ) that was then dried in fluidized beds, first with hot air and then with hot, gaseous hydrochloric acid to produce anhydrous magnesium chloride prills (solid). The plant operated from 1951 to 2002 and reached a maximum production capacity of 50,000 tpa. Originally using IG Farben cells, Norsk replaced them with the high amperage, monopolar diaphragmless electrolyser (DLE) it had developed that ran at higher current efficiencies and resulted in higher cell productivity and operating lifetime.
- Norsk Hydro, Becancour, Quebec, Canada** – converted magnesite rock ( $\text{MgCO}_3$ ) into anhydrous magnesium chloride ( $\text{MgCl}_2$ ). The magnesite was dissolved with hydrochloric acid to produce brine. Anhydrous magnesium chloride production followed the dehydration route at Norsk Hydro's facilities at Porsgrunn. Built in 1989 and using Norsk's DLEs it had a name plate capacity of 40,000 tpy. Startup was punctuated by operational difficulties which required process modifications until desired throughput was achieved. The Becancour

plant was shut down in 2007 as profit margins decreased due to rising labour costs, spikes in energy prices and competition from the Chinese magnesium industry.

- **MagCan, High River, Alberta, Canada** – converted magnesite rock into anhydrous magnesium chloride by reaction of the magnesite with chlorine gas recycled from electrolysis in the presence of carbon monoxide. This reaction was carried out in enlarged IG shaft furnace chlorinator. Planned project capacity was 50,000 tpy to be implemented in several phases. The first module of the plant was built in the late 1980's with a nameplate capacity of 12,500 tpa and began operating in 1990 using modified Russian (VAMI) technology. Technical startup problems, costly equipment modernization, soft magnesium prices and a strong Canadian dollar forced closure of the plant in 1991 after less than a year in operation.
- **Noranda Magnolia Magnesium, Danville, Quebec, Canada** – converted asbestos tailings containing magnesium-bearing serpentine minerals into magnesium chloride. Magnetic separation removed iron from the tailings and subsequent leaching with concentrated hydrochloric acid produced impure magnesium chloride brine. The brine was neutralized in two steps to suppress gelatinous silica formation while allowing for precipitation of other impurities. Following filtration, the purified brine is fed to fluidized bed to produce partially hydrated magnesium chloride ( $\text{MgCl}_2 \cdot 2\text{H}_2\text{O}$ ) granules or prills. These granules were fed into the 'superchlorinator' where they dissolved in re-circulated molten electrolyte that was sparged with hydrochloric acid gas to remove the remaining waters of hydration and reduce any magnesium oxide to magnesium chloride. The molten electrolyte enriched in magnesium chloride was then fed into ALCAN multipolar cells. Commissioning of the plant began in 2000 and took 27 months to get 20-22 out of 24 cells operational. At only 65% current efficiency, plant output was 28,000 tpy despite a nameplate capacity of 63,000 tpa. Numerous technical problems and competition from China rendered further operation uneconomic and forced closure of the plant in 2003.
- **Australian Magnesium Corporation (AMC), Stanwell Magnesium Project, Australia** – is noted among the electrolytic processes although it did not proceed beyond the pilot stage. A process was developed to circumvent the problem of hydrolysis during the preparation of magnesium chloride. Following the production of brine by leaching magnesite with hydrochloric acid, ethylene glycol or methanol are added to the magnesium chloride solution while bubbling ammonia gas to produce solid magnesium hexammino-chloride ( $\text{MgCl}_2 \cdot 6\text{NH}_3$ ). After precipitation and settling, the solids are separated from the liquid phase and

dried where the particles decompose to anhydrous, solid magnesium chloride and ammonia gas; the solids were fed into an ALCAN multipolar cell while the gas was recycled. Piloting of the process was problematic and financing for the venture collapsed.

### Carnallite Electrolysis

The large scale production of magnesium from the electrolytic reduction of carnallite in the Soviet Union was founded with the process developed by the Russian National Aluminium-Magnesium Institute (VAMI) and electrolytic technology licensed from Pechiney. Two plants were initially built in the USSR during the mid-1930's; at Zaporozhye (Zaporozhye Oblast), in western Ukraine in 1935 and at Solikamsk, (Perm Region), Russia in 1936. Additional Soviet plants were built at Berezniki near Solikamsk in 1943 and during the 1960s at Kalush (Ivano-Frankivsk Oblast) in eastern Ukraine and at Ust-Kamenogorsk in Kazakhstan with technological improvements developed by VAMI and the Ukrainian State Titanium Research and Design Institute (STI) based on the operating experience of existing carnallite plants. The key technological developments were the two-stage dehydration process for carnallite, from hexa-hydrate to di-hydrate and from di-hydrate to anhydrous, and the design of the electrolytic cells. In these processes carnallite is first dried with hot air and then melted and treated with chlorine. Natural carnallite sourced from fertilizer producers in the Urals is the raw material for the preparation of anhydrous feed for the electrolytic cell; only at Kalush was synthetic carnallite produced by the reaction of brines sourced from the Kalush-Galenskoye deposit with spent electrolyte containing potassium chloride. With the exception of the Ukrainian Zaporozhye magnesium plant, which was idled in the early 1990s, magnesium production continues at the remaining plants albeit at less than available capacity - Russia production was about 37,000 tpy in 2012 (est. capacity 80,000 tpa), whereas recent nominal production in Kazakhstan has been 20,000 tpy (est. capacity 30,000 tpa) while Ukraine production at Kalush is 2,000 tpy (est. capacity 15,000 tpa). In 1996, Israel Dead Sea Works inaugurated a 30,000 tpa magnesium plant with modernized VAMI/STI technology using natural carnallite harvested from the Dead Sea potash operations. The magnesium plant operates at near nameplate capacity.

### Carnallite vs Magnesium Chloride Electrolysis <sup>[xiii]</sup>

In recent history, magnesium plants using magnesium chloride feed for electrolytic reduction have experienced more operational difficulties than carnallite-based plants. The principal technical challenge in the former is the suppression of the hydrolysis reaction between magnesium chloride and moisture that can produce magnesium oxide as magnesium hydroxychloride or other oxycompounds. Hydrolysis of hydrated magnesium chloride produces highly active hydrogen and oxygen that can react with magnesium chloride to form both insoluble and soluble magnesium oxy-compounds and

gaseous hydrochloric acid. The latter attacks equipment and affects the quality of the chlorine gas generated at the electrode by magnesium chloride electrolysis. Insoluble oxy-compounds cause sludging and effect electrolyte circulation in the cell whereas soluble oxy-compounds take part in competing electrochemical reactions at the anode, accelerating its consumption while also preventing the coalescence of magnesium droplets. To reduce the likelihood of hydrolysis, Norsk Hydro, US Magnesium, and Magnola performed magnesium chloride dehydration in two steps while MagCan attempted to achieve dehydration in one step, although it was not entirely successful. DOW had opted for a 'wet feed' although this resulted in higher specific energy consumption per tonne magnesium produced whereas AMC attempted to circumvent hydrolysis in the feed preparation step by reacting the magnesium chloride brine with ammonia. In comparison, the hydrolysis of carnallite is weaker and a lesser concern, however in these plants there is five tonnes of spent electrolyte generated for each tonne of magnesium product.

#### Thermic Magnesium Production<sup>[xiv]</sup>

In thermal reduction processes, magnesium oxide (as calcined dolomite (CaO.MgO)) is reduced to metallic magnesium by silicon (as Ferrosilicon) or aluminum. The products of reaction are magnesium metal vapor and a dicalcium-silicate slag or dicalcium-aluminate slag depending on the reducing agent. The magnesium vapor is recovered by condensation on a water-cooled surface and then remelted and cast into ingot. The reaction between solid magnesium oxide and the solid reductant is endothermic and slow and therefore requires high temperature and reduced pressure (vacuum) to achieve faster kinetics. Three thermal reduction technologies using silicon as the reducing agent remain in operation today and in order of importance (installed production capacity) these are -

- **Pidgeon Process** – developed by Llyod Pidgeon in Canada in the 1930's and 1940's and operated up until the early 2000's by Timminco (and previously by Dominion) at Haley, Ontario, Canada. Tubular reactors, OD x Length = 3m x 0.3 m, that were horizontally aligned and externally heated in furnace banks with one end of the reactor cooled by a water jacket and connected to a vacuum system. Calcined dolomite mixed and compacted with reductant was heated to approximately 1200 °C under vacuum (10-15 Pa) to produce magnesium vapour and a solid di-calcium silicate slag. The vapor is recovered as a condensed crown, which is then mechanically removed, remelted and cast into ingot. Nominal production of magnesium metal is 10-30 kg per 8 hour cycle. This technology was also used in Japan by Furukawa (1960-1992), Ube (1964-1995) and briefly by Japan Metals (1989) until high labour and energy costs coupled by the strong Yen made production uneconomic. Ube transferred production of magnesium to China where the Pidgeon process was gaining traction in the early

1990s and capacity was in the several thousands of tonnes. Cumulative Chinese capacity by the Pidgeon process has since reached 720,000 – 740,000 tpa. This technology has also been implemented in South Korea by POSCO at its new magnesium facility (15,000 tpa) commissioned in 2012.

- **Bolzano Reactor** – originated from an Amati Furnace that was modified by Edward Ravelli in Bolzano, Italy where it operated up until 1992. The Bolzano reactor is large, refractory-lined, vertical reactor approximately a OD x H = 2 m x 2m with flanged lip at its opening and is capped by bell-shaped condenser. Briquettes of mixed calcined dolomite and ferrosilicon are arranged on a charging tray and lowered into the reactor which is then sealed with the bell condenser. Once sealed and the pressure reduced to 400 Pa, electric resistive heating of the charging tray inside the reactor makes the internal temperature rises to 1200 C producing magnesium vapor and a solid di-calcium silicate slag. After a 22-24 hours process cycle, 2 tonnes of magnesium is recovered onto the bell condenser kept a temperature of 400 – 500 C. At the end of the process cycle, the condenser is removed and reheated to remove the magnesium. The same technology was also adopted by Brasmag (RIMA Industrial) in Brazil in 1979 where it remains in operation and installed capacity has reached 22,000 tpa.
- **Magnetherm Reactor** – developed and operated by Pechiney in Marignac, France from 1964 until 2001 when installed capacity was 20,000 tpa using six furnaces of various sizes. Magnetherm operates at 1300 -1700 C at a pressure range of 400 – 670 Pa; higher temperature compensates when the vacuum in the reaction chamber degrades and what would otherwise translate into a lower rate of magnesium production. Reaction takes place in a molten slag phase that is heated by a centrally-positioned electrode using alternating current. Dolomite, ferrosilicon and alumina are continuously top fed into the slag. Ferrosilicon is the main reducing agent while alumina additions ensure the di-calcium silicate slag remains molten. The magnesium vapor generated during reaction is evacuated and condensed in a molten state and then collected into a crucible by gravity. Depending on the size of the reactor, 3 – 8 tonnes of magnesium is produced per 16 to 24 hour process cycle. This technology was also used by ALCOA subsidiary Northwest Alloys in Addy, Washington, USA from 1976-2001 where installed capacity was 45,000 tpa. The only remaining user of this technology is Magnohrom in Serbia where installed capacity is 8,000 tpa but production is approximately 1,500 tpy.

#### Magnesium Production – Competitive and Strategic Considerations

Industrial philosophy has always tended towards more automation, continuous production and larger scale to achieving better economies. Thermic processes are

batch operated and labour intensive while the process flowsheet and operating technology are relatively simple. Conversely, electrolytic processes, are continuous, more automated and operate with more complex technology and process flowsheets. Consequently, capital investment for an electrolytic plant is estimated as five to nine times higher than a thermic plant per tonne installed magnesium capacity while energy and manpower requirements may respectively be 30%-50% and five times lower for an electrolytic plant on the same basis<sup>[xiv]</sup> - albeit with the caveat that the process might not work. In the early 1990s, China rapidly expanded magnesium production opting for Pidgeon retort technology. Key deciding factors for this choice were the country's abundant dolomite and coal resources, and its large and low-costing labor pool. Pidgeon technology is also robust, proven and simple to build and operate; pilot testing on dolomite feed is only required for proof of principle and to define optimization parameters. Due to the distillation principles exploited in the operation of the retort, very high purity magnesium is produced. In contrast, electrolytic processes, depending on the feed quality and cell design, are more prone to upset particularly for plants based on magnesium chloride electrolysis which can result in higher tramp element deportment to the magnesium and also necessitate process redesigns. Another advantage of batch Pidgeon technology is the ability to modularly expand production by the addition of new retort furnace banks.

Magnesium production has followed the growth in domestic Chinese steel production that was driven by China's economic boom over last two decades. During a recent period of consolidation, smaller, private or undocumented magnesium plants were closed and existing magnesium facilities located near steel plants were enlarged in order to easily source both coal gas fuel and ferro-silicon reductant. Iron and steel making centers use coal gasification to generate coal gas fuel and metallurgical coke. The relatively negligible energy demands of the magnesium smelters compared to these centers allows these fuel transfers at negligible or no cost to the magnesium plant. Coupled with an artificially devalued currency, Chinese magnesium producers operate with distinct economic advantages over foreign competitors. In response to these perceived subsidies, the USA erected anti-dumping tariffs on Chinese magnesium to protect domestic production. Nonetheless, magnesium consumers outside the USA can still source their needs from China.

The concentration of magnesium production in China raises the issue of supply security and the need for diversified sources. Indeed, POSCO established its own Pidgeon plant to produce magnesium in South Korea to reduce reliance on China. Regardless, new installations need to be competitive to Chinese producers. The key prerequisite for green-field plants established outside of China is low-cost energy. Countries in and around the Arabian Peninsula are potential locations given the abundance of natural gas, available dolomite resources and proximity to a number of new aluminum smelters that have cropped up in the region and of course Europe. The discovery of significant



natural gas reserves and decline in natural gas energy prices in the USA also provides the setting for establishing Pidgeon magnesium plants particularly in the south west where there are abundant dolomite resources and depressed economies. Carnallite-based electrolytic plants in the former Soviet Union or CIS also have the advantages of lower-labor costs and access to cheap hydroelectricity. Yet these plants generally operate less for export purposes and in support of titanium production facilities using Kroll-type processes in which magnesium metal reduces titanium chloride to titanium sponge and magnesium chloride, the latter being re-circulated to the electrolytic plant. Brazilian magnesium production is geared for internal domestic consumption and also generally outside the global supply chain.

### Summary

1. The Pidgeon process although labour and energy intensive is simple to operate and produces high purity metal. Its adoption by China in the early 1990s and steady proliferation of Pidgeon plants over the next decade allowed China to become the world's dominant magnesium producer and to displace electrolytic technology as the principal method producing magnesium metal.
2. Electrolytic plants, despite having the advantages of greater automation and lower operating costs, are more costly to build and more complicated to operate particularly in the preparation of anhydrous magnesium chloride or carnallite feedstock. As a result, there is greater financial risk with building and operating electrolytic plants.
3. The speed and relative low cost that Pidgeon plants can be erected is a distinct advantage over electrolytic plants as is the ease of the modular expansion of smelter capacity. Consequently, market penetration and share capture is facilitated. Also, each stage of the process uses mature and proven technology that carries little risk in operation.
4. Economic competitiveness in magnesium production is governed by production costs relative to Chinese export prices. Low or negligible costing energy and artificial devaluation of the Yuan are subsidies Chinese magnesium producers receive that hinder foreign competition. Regardless, the selection of strategic locations outside of China where energy costs are low and there is close proximity to markets can allow for competitive magnesium production by the Pidgeon Process.

## RARE EARTH METALS

Rare earth metals are the sixteen elements of the lanthanide series on the periodic table of elements that stretches from lanthanum (element 57) to lutetium (element 71). In some conventions, the non-rare earths of Yttrium (element 39) and Scandium (element 21) are included due to similar chemical characteristics and coincident end-uses. These high-value, non-commodity metals are critical for the miniaturization of components used in a number of high tech applications that would otherwise be impractical to operate or build with substitute elements. They became the focus of intense media attention and supply scrutiny in 2010 when a collision between a Chinese trawler and two Japanese coast guard vessels in disputed waters escalated to a diplomatic conflagration and rare earth export restrictions from China. Export prices escalated until spiking in mid-2011 but have since been on a decline (Figure 2).

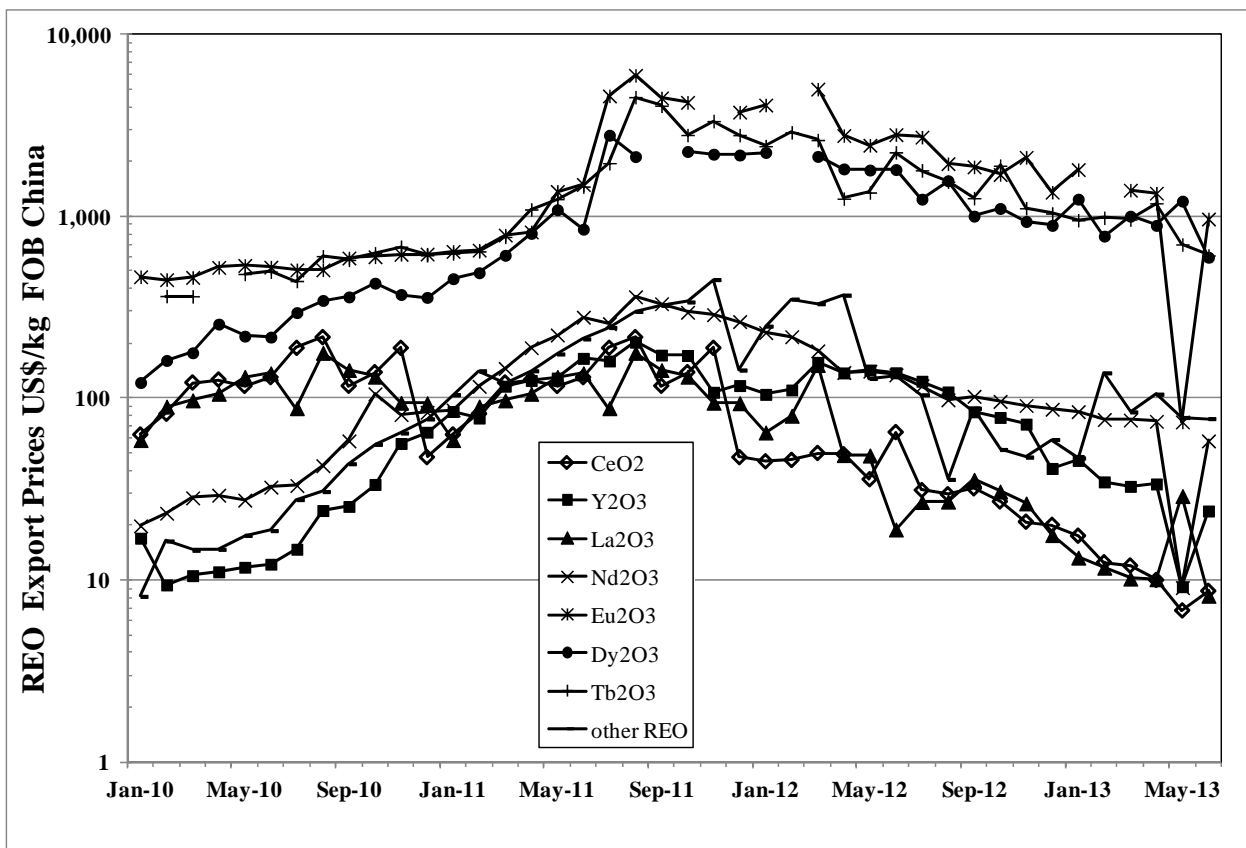


Figure 2 REO export prices in US\$/kg FOB China from January 2010 to June 2013 [source: China Customs].

### Recent Production History<sup>[xv,xvi,xvii]</sup>

Global production of rare earth metals is estimated between 110,000 – 140,000 tpy with 95% of supply attributed to China. The recent history of rare earths production parallels that of magnesium with a shift from mostly Western-based production to rapid

dominance by China over a ten year span. Up until the early 1990s, the US was the largest producer of rare earths principally from Molycorp's Mountain Pass deposit in California that was founded in the late 1940s. Mountain Pass production climbed steadily from 1965 to 1985, which coincided with the time of China's initiative to develop its rare earth resources and high technology sectors. From 1985 to 1995, Mountain Pass output declined while China production ramped up. In 2002, mining operations at Mountain Pass ceased while China rare earth production continued to climb to the presently accounted 95% of global supply. More recently new production has come online outside of China. In 2010, Molycorp reinvested in its Mountain Pass facilities and restarted mining and chemical processing of rare earths in 2012 at a rate of 20,000 tpy. Other new production came from Lynas Corporation's Mount Weld deposit in Australia, with the chemical processing being initiated in December 2012 at the Lynas Advanced Materials Plant (LAMP) in Malaysia at a rate of 12,000 tpy.

Concurrent to the expansion of domestic rare earth production, China also pursued investment in foreign rare earth manufacturing and resource companies to gain access to additional resources and downstream manufacturing technology. In 1995, two Chinese firms, San Huan New Material and China National Nonferrous Metals Import and Export Company (CNNMIEC), acquired a majority stakehold in Magnequench, a neodymium magnet manufacturer founded by General Motors in 1986; the deal was completed in 1997 and, after a five year mandatory period to keep the facilities operating in the US, moved the plant to China. In 2005, Chinese National Offshore Oil Corporation (CNOOC) made a bid to purchase Union Oil of California (UNOCAL) whose assets included the Mountain Pass mine and facilities; this bid was withdrawn following a vote by the US House of Representative that referred the bid to US President George Bush for review due to national security considerations. UNOCAL subsequently merged with Chevron Oil and the assets were spun-off as Molycorp Minerals. In 2009, Australia's Foreign Investment Review Board (FIRB) approved Jiangsu Eastern China Non-Ferrous Metals Investment Holding Co. Ltd, (a subsidiary of the East China Exploration & Development Bureau (ECE)) 25% equity stake in Arafura Resources (Nolan Project, Australia)<sup>5</sup> but later in the year rejected a bid by China Non-Ferrous Metal Mining (CNMC) to acquire a 51% majority stakehold in Australian-based, Lynas Corporation (Mount Weld Project, Australia)<sup>6</sup>.

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<sup>5</sup> Arafura ASX press announcement 29 May 2009,3pp "Australian Foreign Investment Review Board Approves Chinese Investment in Arafura Resources" <http://www.asx.com.au/asxpdf/20090529/pdf/31htmvdvjdzfs.pdf>

<sup>6</sup> Press announcement 24 Sept 2009 "China drops Lynas bid; further strains Australia-China relations" source: <http://www.mineweb.com/mineweb/content/en/mineweb-political-economy?oid=89761&sn=Detail>

## Extraction<sup>[xviii]</sup>

The rare earths label is a misnomer since these elements are relatively abundant in the earth's continental crust at about 175-200 ppm and it is arguably the occurrence of these elements in economic deposits that is rare. Most rare earth production comes from mining of bastnasite, monazite and xenotime as these are the three most commonly occurring rare earth minerals in order of importance.

Rare earths are generally categorized into two groups: light rare earth elements (LREEs) and heavy rare elements (HREEs) although the elements within each group can vary depending on the adopted convention. More commonly, the LREE category spans the sequence of elements from lanthanum to either samarium (element 62) or europium (element 63) with the remaining elemental sequence along with Yttrium considered as HREEs. Grades of potential ore bodies are generally expressed in terms of the total rare earth elements (TREE) concentration, which is the cumulative sum of the individual rare earth assays. It is also common for ore grades, reserves, resources, production data and pricing to be reported in terms of oxides rather than elemental form with lights, heavies and totals being respectively referred by LREO, HREO and TREO (or simply REO).

Beneficiation of rare earth metals depends on the mineralogy of the ore and the particulars are beyond the scope of this paper although the standard methods of crushing, milling, magnetic separation and/or gravity separation and flotation are employed to produce a concentrate of at least 10-20% REO. Following beneficiation, the concentrate undergoes digestion with an acid or caustic solution and the rare earth constituents are precipitated as carbonates, filtered and then calcined into a mixed oxide. One exception are the ion adsorption clays in Southern China enriched in HREOs; these are easily precipitated with an oxalic acid wash and forgo the standard beneficiation practices for hard rock ore. The purified oxide mixture can be sold as a concentrate or further processed into separate oxides. This is performed by dissolution of the mixed REOs with acid followed by multi-stage solvent extraction where the number stages depends on the throughput, the composition of the feed and the desired product recovery stream (individual rare earth streams or combination). Once separated, they are precipitated with oxalic acid or ammonium, filtered and calcined into high purity rare earth oxides which can be subsequently reduced into metal if required.

### Rare Earths Production - Competitive and Strategic Considerations

Rare earth export prices are generally set by China due to its overwhelming dominance in the production and supply of these metals. The rise in rare earth prices, which spiked in mid-2011, and speculation that restricted supply and high prices would be the new

market norm and was the context for explosive growth in rare earth prospecting in the last five to seven years. However, these supply shortages were artificially induced (reversible) by the market intervention of the Chinese government. The export quotas were ostensibly due to increased Chinese domestic demand; it is also arguably a tactic to press high tech industries to transplant their operations and technology to China in order to gain access to raw materials. However, prices have dropped since the peak despite attempts by the Chinese government to stem the decline by curtailing rare earths production and reducing inventory. The downward price trend will likely continue and be further reinforced by any new production centers that come on-line outside of China.

TRU estimates that rare earth production costs in China are generally an order of magnitude lower than what can be achieved in developed economies. Part of this cost differential can be attributed to:

- Artificial devaluation of the Chinese Yuan
- Less stringent environmental, safety and operating standards
- Higher grading REO deposits
- Technological know-how and experience for separating REOs in China

The small size of the REO market as well as the stockpiling of REOs by China is a constraint for any project under development. Given the control that China exerts on export prices, new operations need sufficient operating margin to buffer against soft markets or price manipulation by China. Rare earth export prices are higher than domestic China prices, which is an incentive to bring downstream manufacturers and technology into the country and a caution for new projects that have high operating costs and base their financial analysis on elevated future pricing for REOs.

Some prospects emphasize the HREO proportion (including scandium oxide and yttrium oxide) in the ore body, due to them being perceived as more valuable; ore bodies with at least a 20% HREO component are considered as a heavy rare earth find. However, this perception is misleading and rather the set of strategic or critical set of REOs most important to industry and which command the highest value are the LREEs of neodymium, praseodymium and samarium and HREEs of dysprosium, holmium and gadolinium. Therefore, the product basket of any new project will be an indicator to the financial viability of the project; lower value REOs such as cerium, lanthanum, yttrium and erbium can be considered as commodities that will incur production costs but provide little to the contribution margin to the balance sheet. Revenue reliance on these metals is risky as their relative abundance on the market would likely hinder sale from new production unless discounted.

Following the product basket, the scale of proposed production is another consideration. Some REE projects have announced scales of 20,000 tpy to 40,000 tpy. At these rates, the sudden increase in REE supply could have a disruptive impact on REE prices and

on the project itself especially if it floods the market for a particular high value REE for which global consumption is low. Such projects would become vulnerable to market reaction. Lynas Corp recently opened its processing plant in Malaysia at an operating capacity of 11,000 tpy and has delayed proposed expansion to 20,000 tpa. Similarly, expansion of Molycorp's facility from initial capacity of 11,000 tpa to 20,000 tpa may be delayed to due softening in prices and demand for rare earths.

Proposals to adopt substitute elements to rare earths are not practical for most high end applications; although high prices for these metals are often cited, these are not actual deterrents for end use since the actual proportion of the cost of the REE component is generally small. In next generation wind turbines, permanent neodymium magnets will replace ferrite magnets in the generators; the cost component of these generators was estimated at between 3-4% of the total cost for a 1.5 MW wind turbine requiring approximately 375 kg of neodymium oxide<sup>[xix]</sup>.

The principal motivators for new REE projects external to China are global source security and diversity of supply. Despite the abundance of REEs in the world, the location of many enriched centers outside of developed areas renders exploitation uneconomic due to the investment required to build energy and transport infrastructure, such as the Strange Lake rare earth resources located in northern Quebec and Labrador, Canada and the Greenland Minerals and Energy project at Kvanefjeld, Greenland. Development can also be impeded by environmental, and social and political factors. Some REE prospects carry an elevated proportion of radioactive elements uranium and thorium, which carry environmental and safety liabilities; at Mountain Pass, a radioactive wastewater spill in 1998 led to the temporary closure of the chemical processing plant. Public and political perception of such potential dangers delayed the opening of Lynas Corporation's LAMP plant in Malaysia despite receiving prior government approval. In Burundi, former REE mining operations are being re-examined for renewed exploitation although social and political instability in the country are factors that may pose a risk to secure access of the resource and export of product.

Therefore, the standard by which external projects can be assessed is their competitiveness to other ex-China projects and the rare earth product basket. Although there is some skewed interpretation of projects with a higher proportion of heavy rare earths being more favorable, this interpretation is somewhat faulty as certain light REEs are in high demand while some heavy REEs are not. In TRU projects, the LREEs and HREEs with highest market demand or prospects of sale are the strategic elements on which the foundation of the project should be centered on.

### Summary

1. China's dominant position in rare earths production raises access and security of supply issues for foreign consumers and industries and is motivating the

- development of other REE resources outside of China
2. REE prices are dropping with softening global demand and new output from Molycorp and Lynas
  3. The viability of new projects requires that the proposed product basket and revenue stream be based on the production of strategic REOs, a scale of operation that doesn't flood the market and cause large price upsets and also attaining competitive production costs with respect to China producers

## CONCLUSIONS

Lithium, magnesium and rare earths are niche metals market segments of growing importance to high tech or high value applications. The largest end-uses for lithium and its derivatives are in the fabrication of glass and ceramics, batteries, greases, pharmaceuticals, and rubber and thermoplastics. Magnesium is primarily used for aluminum alloying but a growing proportion has shifted to weight-saving structural material in die-cast parts. Rare earths are critical for the production of compact powerful magnets used in wide array of electronics and electric motors, in battery manufacturing, as phosphors for LED screens and lighting and as chemical catalysts.

The market for these specialty metals is small with production largely concentrated in a few geographical and geopolitical centers. Lithium carbonate production is dominated by three major corporations, SQM, Chemetall (Rockwood) and FMC with raw materials sourced mostly from brines in Chile and Argentina while spodumene concentrate production is dominated by Talison, Australia. Magnesium metal and rare earths production are overwhelmingly based in China.

Diversification and/or security of supply will be an ongoing concern for a number of industries and the motivators for new project development. However, only a few new projects can be accommodated in each of these market sectors. Only those which are the most cost-competitive to current producers, appropriately scaled and financially evaluated on the basis of realistic future demand and metal market prices will have a chance at success.

New primary lithium carbonate producers will likely have higher operating costs than the current three major lithium corporations since no other identifiable resources have been located that mirror the scale or characteristics of the Salar de Atacama in Chile or Salar del Hombre in Argentina Muerto; Salar de Uyuni in Bolivia although a potentially large lithium resource is challenged by its vast expanse, high magnesium to lithium ratio and social and political considerations. Talison's hard rock Greenbushes mine in Australia is also an exceptional deposit with respect to grade and scale unlike any others exploited today or in the recent past.

Magnesium metal production can be competitively produced outside of China with the

Pidgeon Process, provided there is access to low-costing energy such as natural gas sourced in and around the Arabian Peninsula and in the USA.

With new supply entering the market and prices diminishing, rare earths projects outside of China will have to rely on the ability to enter the market at an appropriate scale and focus on the production of the strategic rare earths most in demand for high tech applications.

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