

# LITHIUM, A STRATEGIC ELEMENT FOR ENERGY IN THE WORLD MARKET

Robert Bruce Wallace\*

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## I. INTRODUCTION

This paper does not seek to be ground breaking originality, since numerous commentators and researchers, ranging from reporters, geologists, mining engineers, scientists of different fields and organizations, some economists, and official government institutions such as the United States Geologic Survey (USGS), have delved into the intricacies of the sources, production, demand, prices, competitive industrial structure, and even the geopolitics of lithium, its compounds, and its minerals for a good many years. What the paper does seek is to gather together different dispersed sources of information, both technical and economic, and present a coherent, critical general analysis. Furthermore, though there is unfortunately a lack of sufficient hard data regarding a pending development of what appears to be a huge lithium-potassium deposit in Mexico straddling the limits of Zacatecas and San Luis Potosí, I shall include an analysis of what has been divulged publicly via the internet, most of which is hopeful expectation.

The recent flurry of interest in lithium for use in batteries to power battery electric vehicles (BEVs), hybrid electric vehicles (HEVs), and plug-in hybrid electric vehicles (PHEVs), in addition to more traditional industrial uses, results from a combination of national worries –oil dependency of the net-oil importing major industrialized countries in a context of what some analysts call peak oil and upward tending oil prices, together with public opinion in these countries concerned with global warming induced by growing carbon dioxide emissions. Regarding vehicles, these two perceived fears in the wealthy, technologically advanced countries –oil dependency and environmental degradation—have created political and economic pressure to reduce the consumption of gasoline, both by improving the efficiency of internal combustion engines in combination with electric power (hybrids) and perhaps even eventually supplanting gasoline driven engines with all electric power (BEVs). But, this brings into play the question of which battery chemistry is the most efficient and economically viable in the short and long terms. Lithium-ion (Li-ion) batteries are currently the batteries of choice for EVs, a recent tendency in the automotive industry, but they are certainly not the only possibility as we shall see.

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\* R. Bruce Wallace: Economics professor at the post-graduate department of Economics, Universidad Nacional Autónoma de México, and Geological Engineer (Michigan Technological University, USA). wallace@unam.mx

## II. SOURCES

In accepting that lithium, its chemical compounds and minerals will be deemed strategic for the as yet undefined future, their sources, both geological and geographical, must be studied. This entails the definition and differentiation between reserves and resources. I shall use the USGS definition.<sup>68</sup>

“Resource: A concentration of naturally occurring solid, liquid, or gaseous material in or on the Earth’s crust in such form and amount that economic extraction of a commodity from the concentration is currently or potentially feasible.” Within the resource category there are “Identified Resources” and “Undiscovered Resources”. “Identified Resources: resources whose location, grade, quality, and quantity are known or estimated from specific geologic evidence. Identified resources include economic, marginally economic, and sub-economic components. To reflect varying degrees of geologic certainty, these economic divisions can be subdivided into measured, indicated, and inferred.”

In order to define the category of Reserves, the definition of a subset of Indicated Resources, the Reserve Base is useful. This latter category was employed for many years, but it no longer has been used since 2009 by the USGS, which now only distinguishes between Resources and Reserves.

“Reserve Base –That part of an identified resource that meets specified minimum physical and chemical criteria related to current mining and production practices, including those for grade, quality, thickness, and depth. The reserve base is the in-place demonstrated (measured and indicated) resource from which reserves are estimated. It may encompass those parts of the resources that have a reasonable potential for becoming economically available within planning horizons beyond those that assume proven technology and current economics. The reserve base includes those resources that are currently economic (reserves), marginally economic (marginal reserves), and some of those that are currently sub-economic (sub-economic resources). The term ‘geologic reserve’ has been applied by others generally to the reserve-base category, but it also may include the inferred-reserve base category; it is not a part of this classification system.”

“Reserves –That part of the reserve base which could be economically extracted or produced at the time of determination. The term reserves need not signify that extraction facilities are in place and operative. Reserves include only recoverable materials.” The ‘inferred’ category comprises “estimates ... based on an assumed continuity beyond measured and (or) indicated resources, for which there is geological evidence. Inferred resources may or may not be supported by samples or measurements.

Perhaps a succinct description of some of lithium’s characteristics is in order.\* Lithium (Li) has the atomic number 3 just below hydrogen and helium, and is the lightest metal of the periodic table and least dense solid element. Of the elements of the upper crust of the earth, it ranks 25<sup>th</sup> in quantity, but concentrated, economic deposits are quite rare. Like all alkali metals (including among others sodium and magnesium), lithium is extremely reactive in moist air; that is, lithium in pure metallic form will ignite and burn in oxygen when exposed to water or water vapors. Not only is it flammable, it is potentially explosive when exposed to air and especially to water, which is why lithium metal is often stored under a dense hydrocarbon, such as petroleum jelly. Because of its high reactivity, lithium only appears naturally in the form of compounds. Lithium occurs in a number of pegmatite minerals, but is also commonly obtained from brines and some clays. On a

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\* See lithium via wikipedia.

commercial scale lithium metal is produced electrolytically from a mixture of lithium chloride (LiCl) and potassium chloride (KCl). Lithium is a good conductor of both heat and electricity. Lithium has a low coefficient of thermal expansion and, of solid elements, has the highest specific heat capacity. Because of its specific heat capacity, lithium is often used in coolants for heat transfer applications. Used in lithium-ion batteries because of its high electrochemical potential, a typical battery cell can generate about 3 volts, compared to 2.1 volts for lead/acid or 1.5 volts for zinc-carbon cells. Because of its low atomic weight (6.941 after hydrogen, 1.008, and helium, 4.003), lithium has a high charge and power-to-weight ratio (high specific energy). Lithium batteries are not to be confused with lithium-ion batteries, the latter being high energy-density rechargeable batteries. Other rechargeable batteries include the lithium-ion polymer battery, lithium iron phosphate battery, and nanowire battery. There are many other uses for lithium and its compounds, some of which we will mention later.

It is important to realize that there is an ongoing debate centered on whether the world's lithium recoverable reserves in the future will be adequate through increased production to satisfy not only the 4-5% yearly increase of demand in traditional lithium markets, but also the approximately 20-25% growth of demand for the lithium battery markets, one of which pertains to lithium-containing batteries for the projected dynamically growing electric vehicle (EV) market. In its origin, this debate was initiated by William Tahil of Meridian International Research (MIR) based in France.<sup>33,54</sup> Essentially, his position is that reserves of contained lithium are now and will remain inadequate to satisfy growing demand in the exploding battery market, and, in particular, there will be shortages which will impede the conversion of the world vehicle fleet from gasoline driven internal combustion to EVs, including hybrid electric vehicles (HEVs). Tahil's argument also stresses that substituting oil dependency for lithium dependency, since lithium resources and reserves suitable for batteries are highly concentrated in a few developing countries according to him, could make matters even worse for the highly industrialized countries. Tahil is very much in favor of EVs but stresses the advantages of other battery chemistries such as Zn-air or Zebra NaNiCl batteries (sodium nickel chloride), as we shall see.

R. Keith Evans, a retired consulting geologist with some 40 plus years of experience involved with the lithium business—including representing lithium mining companies and other industrial minerals—vehemently contested Tahil's conclusions of pending shortages, particularly lithium carbonate for the EV market.<sup>10-15</sup> Beginning with Evans' March, 2008 paper "An Abundance of Lithium", and continuing with other papers and internet commentaries, the result of the lithium reserve debate is a striking difference of reserve estimates between MIR and Keith Evans. This difference is partially due to the fact that Evans didn't distinguish clearly between reserves and resources, a fact that he comments upon and justifies in one of his internet postings. Furthermore, Tahil, as director of research at MIR, used the fairly restrictive USGS definitions of reserves and resources, in contrast to Evans who, having been a member of the Lithium Sub Panel responsible for assessing reserves and resources of this element and lithium carbonate in a report of the U.S. National Research Council submitted in the mid 1970s, uses a much less restrictive definition in his present reserve and resource updates, following a 1972 statement by Donella Meadows. "Reserve is a concept related to the amount of material that has been discovered or *inferred* to exist and that can be used given reasonable assumptions about technology and price" (my emphasis on *inferred*, a category not included in the USGS definition of reserves, although it is included in Identified Resources). In addition to Evans' wider definition of

reserves in accordance with Donella Meadows and his not distinguishing between reserves and resources, the result is that Evans focuses on resources, but also “material that may be economical if the price of lithium increases or technology advances to reduce the cost of extraction”.<sup>1</sup>

L. Abell and P. Oppenheimer, in their paper contrasting Tahil and Evans, state that Evans “focuses *exclusively* on the resource estimates”, which in my opinion is not totally correct, but Donella Meadow’s description of reserves followed by Evans does cloud the issues. The upshot is that “MIR’s assertion that the focus should be on the reserve estimates and not so much on the resource estimates is a valid point”<sup>1</sup>. MIR itself states that Evans’ ‘An Abundance of Lithium’ “is not useful for the industrial and strategic planning purposes of the battery and automotive industries. It confounds geological lithium deposits of all grades and types with economically viable Reserves that can be realistically exploited and relied upon as a dependable source of sustainable supply by the mass production scale of the automotive industry” (MIR, 2008, p.2). More to the point, and leaping into more treacherous waters, MIR continues: “Many of the deposits catalogued (by Evans) cannot be considered actual and *potential* Lithium Reserves (my emphasis on potential). They would have higher productivity costs and lower production rates than the South American and Chinese brine deposits, coupled with the unproven and heretofore undeveloped processes”(MIR, 2008, p.2). Abell’s and Oppenheimer’s rejoinder is that “MIR assumes that the market will not accept any increase in lithium material costs”, but if lithium prices increase –and they have increased-- rising costs associated with some presently marginal deposits need not be a restriction on greater supply to meet increasing demand for lithium.

The other reason for the differences in Evans’ and Tahil’s estimates has to do with the geologic differentiation of lithium-containing deposits –brines, hectorite clays, and hard-rock lithium minerals associated with granitic pegmatites, the latter being very coarse-grained igneous rocks “formed by the crystallization of post magmatic fluids” and “in close proximity to large magmatic intrusions” (Evans, March, 2008). As Evans notes, lithium containing granitic pegmatites “are relatively rare and are most frequently associated with tin and the mineral tantalite”.<sup>\*</sup> Quite often the tin and tantalite exploration of pegmatites led to the discovery of the principal lithium bearing minerals, spodumene, petalite, lepidolite

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<sup>\*</sup> Columbite-Tantalite group: Chemical formula of the complex solid solution series:  $(\text{Fe},\text{Mn})(\text{Nb},\text{Ta})_2\text{O}_6$ , i.e., (iron manganese niobium tantalum oxide), the principal ore of niobium (Nb) and tantalum (Ta). Ferroniobium is used in stainless steels and super alloys in jet engine components and heat resisting equipment. Tantalum (Ta) is ductile, highly resistant to acid corrosion, and a good conductor of heat and electricity. It is used in electronic capacitors in portable telephones, PCs, automotive electronics, alloys for carbide tools, among other uses.

and amblygonite.<sup>#</sup> Provided the iron content is low, these minerals are used directly in glass and ceramics manufacturing processes, in the form of ore concentrates. Of the four listed lithium minerals, spodumene is the most common. The extraction of lithium from spodumene or the other lithium minerals is an energy-intensive process.<sup>39</sup> After mining either by open-pit or underground mines, the brute ore is crushed, finely ground, and further beneficiated by a selective flotation process to produce the final concentrate. This concentrate is heated in a temperature range between 1075°C to 1100°C (very energy intensive), which changes the crystal structure of the mineral, making it more reactive with sulfuric acid (H<sub>2</sub>SO<sub>4</sub>). The mixture of finely ground, converted spodumene and sulfuric acid is then heated to 250°C, resulting in lithium sulfate (Li<sub>2</sub>SO<sub>4</sub>). Water is added to dissolve the Li<sub>2</sub>SO<sub>4</sub>, the insoluble material being removed by filtration. The purified lithium sulfate is treated with soda ash (Na<sub>2</sub>CO<sub>3</sub>) forming the insoluble lithium carbonate (Li<sub>2</sub>CO<sub>3</sub>), which precipitates out of solution. The lithium carbonate is separated and dried in preparation for its sale or use by the producer. Lithium carbonate is the most important lithium compound produced from ore deposits and lithium brines because of its use as a feedstock for the production of other lithium compounds.

Because extracting lithium from lithium pegmatite ores is such an energy intensive process, it is significantly more costly than that used for brines. This leads us to the first category of brines, the continental brines.

Continental Brines: As Evans states (March, 2008), the lithium containing brines are mainly derived from the leaching of volcanic rocks. The brines vary greatly in lithium content depending on the intensity and length of time they are subject to solar evaporation, from lows of about 40 ppm (parts per million, 0.004%) lithium in the Great Salt Lake, Utah, where the evaporation rate is modest and fresh water inflow is high, to the high altitude *salares* (salt pans or lakes) of Chile, Argentina, Bolivia and China (including Tibet), where much higher parts per million lithium weight content are common, even reaching more than 3000 ppm (0.3%) in the nucleus of Chile's Salar de Atacama.

Recalling that the extraction of lithium from brines is less costly than the process needed for lithium ores mined from pegmatites, Chemetall Foote's brines at Clayton Valley, Nevada (about 230 ppm of Li) can serve as an example of the lithium extraction process from brines. The brines are pumped from the ground and passed through a series of solar evaporation ponds. When the lithium chloride (LiCl) reaches an optimum concentration, the liquid is pumped to a recovery plant and treated with soda ash (Na<sub>2</sub>CO<sub>3</sub>), thus precipitating the insoluble lithium carbonate (Li<sub>2</sub>CO<sub>3</sub>). The carbonate is then removed through filtration, dried, and shipped. The Chilean and other brines follow a similar

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<sup>#</sup> Spodumene (LiAlSi<sub>2</sub>O<sub>6</sub>) and Petalite (LiAlSi<sub>4</sub>O<sub>10</sub>) are lithium aluminum silicates, spodumene having the higher lithium weight percentage content. Lepidolite, also an ore of lithium, is a hydrous potassium lithium aluminum silicate with the chemical formula: K(Li,Al)(Si,Al)<sub>4</sub>O<sub>10</sub>(F,OH)<sub>2</sub>. These minerals are sometimes associated with economic occurrences of cesium (Cs) and rubidium (Rb). The chief ore mineral of cesium is Pollucite, a hydrous cesium sodium aluminum silicate (Cs,Na)<sub>2</sub>Al<sub>2</sub>Si<sub>4</sub>O<sub>12</sub>·H<sub>2</sub>O. The largest known deposit is in the spodumene pegmatite at Bernic Lake, Manitoba. It is also found in Zimbabwe. Principle uses: as a brine of high density, low viscosity for high pressure/high temperature oil and gas drilling; used in cesium atomic clocks having a vital role in Global Positioning Satellites (GPS); internet and cell phone transmissions; aircraft guidance systems; cesium-131 and cesium-137 used in cancer treatments; industrial gauges; used in mining and geophysical instruments; sterilization of food, sewage and surgical equipment: can be used in ferrous and non-ferrous metallurgy to remove gases and other impurities (USGS, 2010). Price quotes (2010) USGS: 1 gm ampules, cesium 99.8% pure \$US 52; 1 gm ampules, cesium 99.98% pure \$64. Cesium and Rubidium can be used interchangeably in many applications.

process, only being slightly adjusted for different chemistries.<sup>39</sup> The use of solar evaporating ponds considerably reduces the cost of energy and the lithium containing brines avoid the crushing and grinding costs of lithium hard rock ore processing.

Geothermal Brines: Although small quantities of lithium are contained in geothermal brines located in New Zealand, Iceland and Chile (ranging from 8 to 47 ppm), the most attractive known occurrence is the Salton Sea area of Southern California, where the brines average about 200 ppm lithium content (0.02%)<sup>10</sup>.

Oil Field Brines: Large tonnages of lithium are found in the oil field brines of the Smackover formation stretching from North Dakota through East Texas and Arkansas, but the East Texas and Arkansas brines, with average ppm of 386 and 365 respectively<sup>33</sup>, appear to be the most promising, though Evans mentions<sup>10</sup> that there are oil field brines grading up to 700 ppm.

Hectorite Clays: Hectorite, a lithium bearing member of the montmorillonite group of clays, is a hydrous magnesium lithium silicate, with chemical composition  $(\text{Mg,Li})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ . Evans informs us that these clays are found in a number of areas in western U.S., but that the largest deposit where drilling has confirmed very large tonnages is located in a volcanic caldera on the Nevada/Oregon border.<sup>10</sup> MIR essentially does not analyze this potential resource in its 2006 and 2008 papers. Evidently MIR does not consider this hectorite deposit worthy of inclusion in lithium resources.

Jadarite: A huge jadarite deposit in Serbia, discovered by Río Tinto Zinc Corp., was estimated to contain more than 850,000 tonnes of contained lithium and, according to Evans, the total reserve could at least be doubled once the deposit is thoroughly explored.<sup>10</sup> Here again, Evans considers the deposit a *reserve*, not a *resource*. MIR does not mention this resource at all, perhaps because the information of its existence was made public after MIR published its research.

### III. RESERVES AND RESOURCES

Since there is such a difference between MIR's estimate of resources and reserves and Evans' estimate, as well as other authors' calculations, I shall essentially use a revised presentation of Abell's and Openheimer's data.<sup>1</sup> Why revised? Because I cross checked their data with Tahil's and Evans' dispersed data and found several discrepancies. Let's take Tahil's lithium content resource estimates as of his May, 2008 paper<sup>33</sup>, and compare these data with the breakdown of Evans' March 2008 global estimate of 28.4 million tons lithium content, while simultaneously presenting instances of the often acerbic criticism leveled one against the other regarding particular deposits of lithium. First off, it's important to remind ourselves that the estimation of resources and reserves is a hazardous business, resulting in wide ranges among different authors.

Salar de Atacama: This salar (salt pan), with an area of approximately 3,500 km<sup>2</sup> in northeast Chile in the Atacama desert area, is, in words of Tahil, the "highest quality (brine) lithium deposit in the world". According to Tahil, there are 3.0 Mt (million metric tons) of lithium contained metal resources (reserve base), of which 1Mt are estimated to be recoverable reserves. MIR's (Tahil's) reserve base estimate of 3Mt apparently is taken directly from the USGS former estimate, which takes into account not only the 30km<sup>2</sup> epicenter of the Salar de Atacama, with some 3000 ppm, but also the rest of the nucleus with a lower average concentration, 1500 ppm according to Tahil<sup>54</sup>. MIR calculated a 450,000 lithium content resource for the 30km<sup>2</sup> epicenter, considering a maximum feasible

depth of 35 meters for the brine, 10% porosity, and a brine specific gravity of 1.2g/cc. This means that Abell and Oppenheimer erred in their criticism that MIR “only considers the 30km<sup>2</sup> epicenter”. From the resource figure of 3MT, and using a 50% recovery factor, MIR placed an upper limit for recoverable reserves of 1Mt of contained lithium, but this upper limit depends very much on MIR’s assumption that below about 35 to 40 meters the halite is “a solid mass devoid of any pores”, which means that “there is no lithium to extract below the current pumping depth, only solid rock salt”.<sup>33</sup> This affirmation of a lower limit of brine occurrence has been vigorously refuted by Evans, as we shall see, but before doing so, other positive characteristics of the Salar de Atacama, which help to make its products more competitive, should be mentioned. When the Mg/Li ratio in a brine is too high, the evaporation rate is reduced which leads to a lower lithium yield. In the case of the Salar de Atacama, MIR’s estimated average Mg/Li ratio is a fairly high 6.4, but this relative disadvantage is compensated by the extreme aridness of the area and a not too high elevation above sea level, 2300m (about the same as Mexico City), resulting in a high average evaporation rate of more than 3.6m per year. Extremely high elevations reduce the evaporation rate of the brines. Low evaporation rates mean that the area of the evaporation ponds would have to be greater to increase the grade of the plant feed and, therefore, capital costs would be higher. The average 1500 ppm of contained lithium reported by MIR (0.15%), if compared to the other important brine resources, is also very high. Higher grades also reduce capital costs.

Keith Evans, in his March, 2008 report, estimated the lithium tonnage for the Salar de Atacama as a whole, arriving at a figure of 6.9Mt. This figure represents the sum of the estimates for the two companies engaged in exploiting their claims in the salar, Chemetall and SQM (Sociedad Química y Minera de Chile), the zone between their claims, “and a portion of the area to the north of the nucleus ... where lithium values remain high –higher than at the Bolivian and Argentina salares”<sup>11</sup>. Later he was advised by Chemetall to increase his initial estimate by 100,000 tons, so the total resource estimate for the salar was 7.0Mt. It’s important to add that SQM had completed extensive additional drilling and bore hole monitoring below MIR’s supposed maximum of 40 meters for the presence of brine. This resulted in SQM’s updated 2008 resource estimate of 6Mt contained lithium, which Evans accepted. Obviously, Tahil erred in stating that it’s geologically impossible for brines to exist below 40 meters of depth. This will be made even clearer when we look at the Salar del Hombre Muerto in Argentina. In Table 7, Appendix A of Abell’s and Oppenheimer’s paper, Evans’ lithium resource estimate should be changed from 6.9Mt to 7.0Mt.

Salar del Hombre Muerto: Foote Mineral Company (FMC) began producing lithium in Argentina’s Salar del Hombre Muerto, about 220km southwest of the Salar de Atacama, in 1997-98. Tahil’s resource figure of 0.8Mt of contained lithium is based upon Donald Garret’s estimate for 2004<sup>19</sup>, which “appears reasonable” to Tahil taking into consideration the size of the salar, its average grade of 0.062% (620ppm), and its very low Mg/Li ratio of 1.37, although the salar is much smaller than the Salar de Atacama. On the other hand, the salar’s high altitude (3,700m) determines a lower evaporation rate (2.7m/year) than at the Salar de Atacama.<sup>33,54</sup> From the resource figure, Tahil estimates recoverable reserves to be about 0.375Mt contained lithium. Tahil mentions that “brine can be extracted from lower depths than in many other salares”, meaning at lower depths than he considers possible at the Salar de Atacama. Why this is impossible in Atacama but is feasible in Hombre Muerto he doesn’t say. Evans emphasizes that “about a third of the reserve at Hombre Muerto (is)

at a depth of between 40 and 70 meters –a depth that Tahil says is too great for brines to be present”. Nevertheless, Evans does state that Tahil’s figure of 0.8Mt is acceptable, but he adds that “an extensive drilling program ... determined average porosity and the lateral and vertical variation in brine grade”, but Evans again refers to this resource as a reserve, which is debatable. Abell’s resource figure for Evans is 0.85Mt, close to Tahil’s estimate.

Salar del Rincon: Also located in Argentina 130 kms north of Salar del Hombre Muerto, the Australian company Admiralty Resources (ADY) began developing this resource in 1999. The salar is less attractive than both the Salar de Atacama and Hombre Muerto, with an average lithium content of approximately 0.033% (330 ppm) versus 1500 ppm and 620 ppm respectively, although 330 ppm is higher than at the last active brine operation in the United States at Clayton Valley, Nevada (230 ppm). Rincon’s Mg/Li ratio is also higher at 8.61, but much less than the Mg/Li ratio (18.6) at the giant Salar de Uyuni in Bolivia as we shall see. This, plus the high altitude of the salar (3,700m as at the Salar del Hombre Muerto), reduces the evaporation rate, leading to more production time and higher costs of reagents to reduce the magnesium content so that lithium chloride can be formed in the brine. ADY does this by “pre-treating the raw brine with calcium hydroxide to remove magnesium and then treating with sodium sulfate to remove calcium”<sup>33</sup>. This is done before the brine is pumped to the solar evaporation pond, where the resulting LiCl can be concentrated before eventually treating it with sodium carbonate in order to precipitate and extract the insoluble lithium carbonate.

Tahil, after much analysis of ADY’s July, 2007 updated lithium metal reserve estimate of 1.4Mt, believes it’s prudent to revert to the 2004 recoverable reserve lithium content estimate for ADY performed by Chilean geologist Pedro Pavlovic<sup>48</sup> of 250,000 tonnes, which was based on an estimated porosity of 8 to 10%. Firstly, Tahil makes clear that the 1.4Mt are not recoverable reserves but a resource estimate. Secondly, he questions the figure itself, since it was based on ADY’s reported 38% average porosity, calculated after an extensive drilling program which found large brine containing cavities, whereas the crystalline mass of the salar has a porosity varying between 3 and 8%. Tahil infers that some of the cavities are interconnected, but probably not all of the cavities, which means that, if a well happens to enter a connected cavity system, “once it has been emptied, it will be subject to the 3% - 8% porosity and related low permeability” of the brine in the crystallized mass. “Therefore, even if the average porosity is 38%, leading to a higher amount of Lithium overall in the salar, this does not necessarily mean that the recoverable reserve ... can be increased accordingly.”<sup>33</sup> So, does Tahil consider the 1.4Mt estimated by ADY as the quantity of resource? Apparently not. In his 2007 report he specifies “Li resources of 0.48Mt in the Salar de Rincón”<sup>54</sup> (approximately 0.5Mt), with a recovery factor of 50%, resulting in the Pavlovic figure of 0.25Mt of recoverable reserves. In Abell’s and Openheimer’s Appendix A, instead of 0.5Mt in the resource column, they published 5.5Mt, obviously a typing mistake, and in the Li reserve column, they put 0.6Mt.<sup>1</sup> Where this figure comes from, I don’t know. It should be 0.25Mt (250,000 tonnes). What about K. Evans? In his July, 2008 blog, Evans admits he erred when reporting 1.86Mt of reserves, the highest of a range of estimates by ADY. He later reduced Rincon’s estimated tonnage by 0.46Mt, resulting in the final figure reported by ADY, 1.4Mt. Evans justified this final high estimate stating that “the reason of course is that earlier estimate (by ADY) was made when only a small portion of the salar had been drilled and there was no site-specific porosity data” although he did add that “there is ... some concern about the role played by the reported cavities that significantly increased the overall porosity of the aquifer”<sup>11</sup>. In

other words, Evans may have some doubts about the quantity of recoverable reserves too. Nevertheless, it is still reasonable to suspect that after much more exploration drilling the figure of 0.25Mt of recoverable reserves quoted by Tahil is strongly underestimated. Finally, Abell and Oppenheimer should have put 1.4Mt and not 1.86Mt in the column of resources for Evans corresponding to the Salar del Rincón.

**Salar de Olaroz:** This salar is located near the larger Salar del Rincón in northern Argentina and is being explored by the Australian firm Orocobre Ltd. Tahil mentions that apparently Olaroz's lithium grade is higher than that at Rincón, with 900 ppm versus 330, and that the projected resource is about 0.325Mt of contained lithium metal, based on an estimated porosity of 10%. At a 50% recovery rate, there would be only about 0.16Mt of recoverable reserves. Both figures are included in Abell's and Oppenheimer's paper.<sup>1</sup> Evans also included a preliminary estimate for the Salar de Olaroz, 0.3Mt of contained lithium, which was not incorporated in the Abell-Oppenheimer report, but should be added. As Evans did not distinguish between resources and reserves, there will be only a figure in the resource column.

**Salar de Uyuni:** The Salar de Uyuni is the largest salar (approximately 10,000km<sup>2</sup>) and lithium deposit in the world, with a contained lithium resource of approximately 5.5Mt according to Tahil, who had taken the figure from Evans' reserve estimate, noting again that Evans should have designated the 5.5Mt as a resource and not as reserves. The USGS resource estimate for 2008 was 5.4Mt. These resource estimates are for the entire 10,000km<sup>2</sup> salar, taking into consideration an average contained lithium concentration of 0.035%<sup>(54)</sup>, as well as other factors mentioned below for the epicenter. What was Tahil's reserve estimate? That depends on the area considered, the estimated average depth of the lithium containing brine, the brine density, and the average porosity. Since it would be impossible to exploit the entire salar which varies greatly in lithium grade throughout its extent, from some areas with lower but respectable levels of 500 or so ppm to small concentrations that can reach as high as 4700 ppm, obviously production will take place initially in what's considered the epicenter, which Tahil assumes to be about 200km<sup>2</sup>, with a lithium concentration of 2000 ppm, an average brine depth of 3.5m, 35% porosity, and a brine density of 1.2g/cc. Working out the math, the result for this area is approximately 600,000 tonnes of contained lithium resource. Applying a recovery factor of 50%, Tahil arrives at 300,000 tonnes (0.3Mt) of recoverable reserves.<sup>33</sup> However, the recoverable reserve figure Tahil puts in his Table 4 (Tahil, 2008, p40) is doubled to 0.6Mt. He doesn't explain why he now considers these 0.6Mt the recoverable reserve and not the resource of the 200km<sup>2</sup> assumed epicenter. At any rate, Abell and Oppenheimer accept this figure as the recoverable reserves for the Salar de Uyuni.

Although the lithium resource of 5.5Mt is huge –Tahil says it is more than 40% of world lithium brine resources, which Evans strongly refutes—and the average porosity of 35% is very advantageous, the extremely high Mg/Li ratio of 18.6, as we saw, impedes the formation of LiCl unless magnesium is extracted before the brine is pumped to the evaporation ponds. This, of course, increases the costs of processing. Evaporation is also relatively retarded due to the high elevation of the salar (3,653m) compared to the 2,300m elevation of the Salar de Atacama. The estimated evaporation rate is 1.5m/year compared to the 3.6m/year at Atacama. Because the highly porous halite in the Salar de Uyuni has only a depth which varies from 2 to 5 meters according to Tahil, with a maximum thickness of only about 11m, “the quantity of lithium available per unit surface area is much lower than in the Salar de Atacama” and, therefore, “a correspondingly greater area of the salar will

have to be exploited for an equivalent Lithium production”.<sup>33</sup> An additional handicap is due to the seasonal flooding of the entire salar, which dilutes the lithium grade and means the solar evaporation ponds must be larger. All of these negative factors will cause extraction costs to be relatively higher than they otherwise would be.

Evans states that Tahil’s description of the Salar de Uyuni is “substantially correct”, except that “it doesn’t contain over 40% of global lithium brine resources”<sup>11</sup>. Furthermore, as with most continental brines, lithium is often associated with potassium, which in the case of the Salar de Uyuni has an average grade of 0.72% based on a 1981 joint exploration effort by a Bolivian and French team.<sup>11</sup> As Evans states, “the percentage of reserves that can be economically recovered will be dependent upon the prices of both lithium and potassium chloride”, as well as the costs associated with the physical characteristics of the salar.

Clayton Valley, Nevada: Foote Mineral Co. (FMC) began producing lithium at Clayton Valley (known also as Silver Peak) in 1966. This company was later purchased by Cyprus Minerals, then Cyprus by Chemetall, a German company, and finally Chemetall was taken over by Rockwood Holdings of New Jersey. The salt pan is only about 50km<sup>2</sup> and presently has an average lithium content of only 230mg/l (that is 230 ppm). The evaporation rate is a low 0.9 meters/year –later 1.8m is specified-- but Clayton Valley is favored by a low Mg/Li ratio (1.43), comparable with the Salar del Hombre Muerto. Its ongoing production indicates that the operation is still economically viable. According to Tahil<sup>33</sup>, the remaining contained lithium resource is 0.3Mt with a recoverable reserve of 0.118Mt, the latter figure being considerably higher than the “economic reserves” of 40,000 tonnes reported by Evans<sup>10</sup>. Abell and Oppenheimer placed this figure in the column of lithium resources, although it may be more appropriate to think of the 40,000 tonnes (0.04Mt) as reserves. Nevertheless, since all of Evans’ other sources of lithium are being considered resources, I’ll continue with this interpretation.

#### Chinese Brine Resources:

Zhabuye Salt Lake, Western Tibet: This remote salar is located at the very high altitude of about 4,400m, which results in lower evaporation rates than at the Salar de Atacama, but the compensating factors are a high average lithium content (0.12%, i.e. 1,200 ppm) and an apparently low Mg/Cl ratio. Tahil estimates the total resource at Zhabuye to be 1.25Mt contained lithium metal and recoverable lithium metal reserves at 0.75Mt, although I can find no justification for these tonnages.<sup>33</sup> Evans, on the other hand, seems not to have ventured an estimate. Strangely enough Abell and Oppenheimer (A&O) did not include Tahil’s estimates in their Appendix A of Active Lithium Mining Operations, although they do report production figures of lithium carbonate equivalents from Zhabuye.<sup>1</sup>

The East Taijinaier Salt Lake, Qaidam Basin, Qinghai Province, North of Tibet: The Taijinaier Salt Lake, developed in the early 2000s, is apparently the largest yet discovered in China. Although Tahil does not have an estimate for its average grade nor its Mg/Li ratio, apparently this ratio is quite high according to Evans. Nevertheless, Evans also states that technological breakthroughs for treating brines with a high Mg/Li ratio have led to the viability of the large Chinese brines,<sup>11</sup> though in a later blog Evans rectifies this opinion, stating that the Chinese “are having serious problems with the high magnesium/lithium ratios in two of their brine sources”<sup>12</sup>. Tahil estimates the total lithium

metal content of the Taijinaier resource to be 1.0Mt and the recoverable reserve 0.5Mt, again without an explanation.

The DXC Salt Lake, Western Tibet: This lithium resource is much smaller than the former two Chinese brine deposits, but it has the advantage of a very low Mg/Li ratio of only 0.22, while the average lithium metal content is 0.04% (i.e. 400mg/l), which is much higher than the 230 ppm at Clayton Lake. But the cold atmosphere at 4,475m also means that the evaporation rate is considerably lower than at the Salar de Atacama. Perhaps the greatest difficulty is its remote location in Tibet, more than 600 kms of rough roads from the nearest rail head, as Tahil reminds us.<sup>33</sup> Tahil's estimate of the lithium metal resource equivalent is 0.16Mt (i.e. 160,000 tonnes). With a recovery factor of 50%, his reserve estimate is 0.08Mt. Again, Evans provides no estimate for this Chinese salar, but he does present a range of quoted reserves for the total of Chinese brine deposits "as being between 2.6 and 4.8 million tons of Li", although in reality these figures represent total brine *resources*. Tahil's total for the 3 brine deposits described above comes to 2.41 million tonnes, which is fairly close to Evans' lower quote of 2.6Mt. A&O use this latter figure as Evans' estimate of total Chinese brine resources.<sup>1</sup>

Other Continental Brine Deposits: Evans states that he did not include any of the following brine sources in his estimates because of their low grades: Searles Lake in California, the Great Salt Lake in Utah, the Bonneville Salt Flats, the Dead Sea in Israel, and Sea Water.<sup>11</sup> Under the heading Future Potential Resources, Tahil did include them "seemingly to dismiss them as potential sources",<sup>11</sup> according to Evans.

Searles Lake: The central section of this small 100km<sup>2</sup> salt lake 200km north of Los Angeles has a grade varying from 50 to 80 ppm with grades even lower toward the edge. The higher quality brines were depleted by 1995 after many decades of production. Tahil estimated the remaining resource at only 18,200 tonnes of lithium, taking into consideration the area of the salt lake (100km<sup>2</sup>), the depth of the brine laden halite (8m), a very high porosity (35%), and a high brine density of 1.3g/cc.<sup>33</sup> Tahil's conclusion is that the brine deposit "is too small a resource at too low a concentration to be economically viable". A&O, nevertheless, put Tahil's rounded 20,000 tonnes of remaining Li content (0.02Mt) in the resource column of Future Lithium Mining Operations,<sup>1</sup> although renewed production remains doubtful. Evans, likewise, did not include the Searles Lake brine in his global lithium content estimate of reserves and resources.

The Great Salt Lake, Utah: Ranging from about 18 to 64ppm, there has been no production of lithium, although "solvent extraction or selective crystallization" technologies have been tested which led to estimates of only about 40 tonnes per year of lithium metal from the potassium sulfate plant. Besides, important tonnages of K<sub>2</sub>SO<sub>4</sub>, NaCl and MgCl are also produced at the GSL after concentration in two 10,000 hectare ponds, where the evaporation rate is about 1.8m/year, about half that of the Salar de Atacama. The principal drawback for lithium extraction is the 250:1 Mg/Li ratio. In spite of these obstacles, Tahil cites a 0.526Mt lithium metal resource estimate and recoverable reserves of 0.283Mt, though it's clear that he doesn't believe these reserves will be exploited. Abell and Oppenheimer only include 0.53Mt in their resource column of Future Lithium Mining Operations, and also attribute to Evans 0.52Mt in the same column, although Evans states he didn't consider the GSL in his global estimate, which means that the 0.52Mt should be removed.

The Bonneville Salt Flats, Utah: The very high Mg/Li ratio of 100:1 means that recovery of high purity lithium is very difficult<sup>33</sup>, which probably explains why lithium has

never been extracted from the Bonneville brines. Tahil excluded this salt flat from his lithium resource estimate. Nor did he include the Dead Sea of Israel. Its Mg:Li ratio is even higher (2000:1) and the low lithium concentration (10-20 ppm) of the brine is decidedly another negative economic factor. Sea Water as a source of lithium, although scientific extraction research is ongoing, presents even more challenges, with an average concentration of about 0.000017% (0.17 ppm) and nearly a 7000 Mg/Li ratio. Therefore, it is not included in Tahil's resource estimate.

#### Geothermal Brines:

The Salton Sea Known Geothermal Resource Area (SSKGRA): Presently the largest geothermal source of electrical power in the U.S., the Salton Sea KGRA has a lithium content ranging from 100 to 250ppm, with an estimated average of about 200ppm, slightly less than at Clayton Valley, Nevada. Tahil informs us that at a brine density of 1.2g/cc and an estimated brine volume of 4km<sup>3</sup> this underground brine would contain about 0.96Mt of lithium resource, rounded to 1Mt.<sup>3</sup> Tahil, in a long analysis of the brine potential based on the Simbol Mining Company's hoped for production of 100,000 tpy of Li<sub>2</sub>CO<sub>3</sub>, attempts to convince the reader how really difficult it would be not only to reach the planned yearly production rate but even to come on stream with the project. He, therefore, presents no reserve estimate. Nevertheless, Evans is right when he says that "Tahil seems to accept that oil field brines and geothermal brines could have some potential"<sup>11</sup>. It should be mentioned that the brine contains other metals such as lead, zinc, manganese, strontium and tin; Evans mentions potash (KCl), boron, zinc and lead. Evans also accepts a lithium grade of about 200 ppm, and based on a throughput of brine per year containing 16,000 tpa lithium with an assumed 20 year life of the operation, arrives at a reserve tonnage of 316,000 tonnes of lithium (0.316Mt)<sup>10</sup>, which Abell and Oppenheimer correctly assign as a resource in their Future Lithium Mining Operations. However, A&O did not include the Tahil resource figure of 1Mt in their paper, which seems to me to be an error.

Oil Field Brines: Although some of the world's oil field brines contain moderate concentrations of lithium, Garret states that perhaps the most promising up to the present is the Smackover brine, particularly in East Texas and Arkansas, where the grades average 386ppm and 365ppm respectively.<sup>19</sup> In the Smackover formation of Arkansas oil fields, the ground water brine occupying the pores is being economically exploited for its immense quantity of contained bromine,\* while the attractive potential of lithium hasn't been exploited and which, according to Evans<sup>11</sup>, is an enigma regarding any kind of investigative work. Tahil estimated the yearly potential lithium that could be extracted from the Arkansas brine where the bromine industry is fully developed. Based on an average brine flow rate of 320Mb/year (million barrels), an average lithium content of 365ppm, a specific gravity of 1.2g/cc, the yearly extraction of lithium would be in the order of 22,000 tonnes. Tahil doesn't make clear how he arrived at a total contained lithium resource in the Arkansas oil brines of 1Mt. But considering a potential of 20,000 tonnes/year and assuming 50 years of life for the operation, the resource total would come to the reported 1Mt. But potential

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\* Uses of bromine compounds: flame retardant although in decline for environmental reasons, drilling fluids in oil and gas applications, bromated pesticides, water treatment, dyes, insect repellents, perfumes, pharmaceuticals, photographic chemicals and other chemical products. A new market for bromine is to bond with mercury emissions in coal-fired power plants, as mercury bromide (HgBr), which is more easily captured in flue-gas scrubbers than the usual mercury chloride (HgCl). Prices were up in 2010 because of Chinese demand, energy prices, regulatory compliance, raw materials, and transportation price rises (USGS, Commodity Summaries).

recoverable reserves per year, according to Tahil, would be 11,000 tonnes. However, Tahil is not optimistic about this potential being produced because of a possible conflict over water rights with other numerous users. The extraction of bromine now requires a huge amount of water from the local aquifer. Extracting lithium with selective absorption technology, which requires large amounts of water, could intensify the competition due to a worsening water situation. For this reason, Tahil doesn't include the reserve estimate, nor do A&O. Evans accepts "a possible reserve of 0.75 million tonnes"<sup>11</sup>, which again should probably be judged the lithium resource in the Smackover Formation oil field brines of Arkansas.

#### Lithium Containing Pegmatites:

Until 1997 most of the production of  $\text{Li}_2\text{CO}_3$  was processed from spodumene and other hard rock lithium minerals found in some pegmatites. When SQM began producing low cost lithium carbonate from its Salar de Atacama brines, it reduced the price of carbonate by a half thus causing lithium carbonate production from pegmatite sources to be uneconomic. Mines such as Greenbushes in Western Australia, the Kings Mountain and Bessemer City mines in North Carolina, and the Pervomaisky mine in Russia were closed. Perhaps this is the reason that Tahil doesn't include these and some other pegmatite sources of lithium in his estimates of resources and reserves. Another probable reason is that Tahil categorically states that "Only Lithium from the Brine Lakes and Salt Pans will ever be usable to manufacture batteries: the Spodumene deposits can play no part in this"<sup>54</sup>. This opinion is seriously questionable. Evans' opinion is that should the demand for lithium carbonate increase significantly, especially for the high grade (99.95% purity) needed in the expanding battery industry, the spodumene sources will be reactivated and developed. He adds that, of course, prices will have to increase sufficiently to justify the necessary investments at these spodumene sources.<sup>11</sup> The upshot of the issue is that with sufficient price increases of lithium the lithium bearing pegmatite mines could again become competitive and profitable. For this reason, I agree with Evans that lithium resource equivalents from pegmatite deposits should be included in global estimates. However, Evans is not strictly correct when he criticizes Tahil saying he only references the smallest and lowest grade lithium containing pegmatite deposit at Osterbotten in Finland. Tahil also includes other pegmatite resources: Mt. Cattlin in Australia and Bikita in Zimbabwe. Nevertheless, Tahil did not include the lithium content resource nor reserve figures of any pegmatite in his Table 4.2, Lithium Carbonate Production.<sup>33</sup> As a first example, Tahil only considers one small pegmatite source in China, Jiajika, without including his resource estimate of 6,000T of contained lithium in his Table 4.2<sup>33</sup>, while Evans estimates lithium reserves from pegmatites in China at 750,000 tonnes (.75Mt).<sup>11</sup> This figure should be included in A&O's resource column for Evans.

As I mentioned, Tahil doesn't bother to estimate the resource and reserve tonnages for Greenbushes in Western Australia, 300 km from Perth, even though he describes it as "the largest and highest grade Lithium hard rock mineral resource in the world"<sup>33</sup>. Evans, on the other hand, had estimated Greenbushes' lithium reserves at 223,000 tonnes<sup>12</sup> (0.223Mt), whereas A&O mistakenly read and put 0.243Mt in their resource column<sup>1</sup>, unless Evans himself had erred in his blog. Probably the 0.223Mt should be placed in the lithium reserve column, since in the National Research Council reports "adjustments (were made) to the gross tonnages of the pegmatites to allow for mining and processing losses. In the case of anticipated open pit operations (such as Greenbushes) the tonnages were reduced by 25% and by 50% in the case of anticipated underground projects"<sup>13</sup>. However,

since Evans does not distinguish between reserves and resources, I'll continue the precedent of putting all Evans' estimates in the resources column, as A&O do. After A&O published their December 2008 paper, Talison Minerals, a spinoff company formed by a group of investors who purchased Sons of Gualia's Greenbushes pegmatite, increased exploration activity, resulting in new reserve estimates of 1.5Mt of contained lithium. This figure was presented by Talison at the January 2009 Santiago Conference "Lithium Supply and Markets" organized by Industrial Minerals magazine. The question again is whether the tonnage of 1.5Mt accepted by Evans should be considered a resource or reserve. Interestingly, in Evans' August 2009 blog, the figure for Talison's Greenbushes, though said to have had a tripling of reserves, had been reduced to 1Mt of contained lithium. It appears that Talison was now more conservative in its reserve estimate. I shall take into consideration these updated figures (as resources?) but only after using the data that A&O had (or should have had) access to.

Regarding the Mt. Cattlin tonnages of contained lithium, A&O again erred by placing Tahil's lithium carbonate tonnages in their Table 9 (Former Lithium Mining Operations) instead of lithium metal equivalents. The resources should be 0.066Mt and the reserves 0.033Mt instead of 0.35Mt and 0.15Mt respectively. The correct figures are derived from Tahil's stated "24.8MT of ore at 0.56%  $\text{Li}_2\text{O}$  content"<sup>1</sup>. A&O assigned Evans' 20,000 tonnes Li content to the resource column. I personally haven't been able to find this figure in Evans' internet blogs but shall assume it's correct, and, furthermore, note that the 0.02Mt are best kept in the resource column, since Evans clarifies that for the "moderate sized pegmatites, the in situ tonnages are given" as are the in situ tonnages given for all the brines since "recoveries vary greatly"<sup>11</sup>.

As I mentioned before, Tahil doesn't provide lithium resource and reserve data for the North Carolina pegmatites, but he does admit that these pegmatites theoretically could be re-developed both as a response to reducing dependence on foreign oil and subsequently reducing dependence on foreign lithium, "though it cannot be as economic as brine"<sup>33</sup>. True, it cannot be as economic as the better brine sources of lithium, but, as Evans emphasizes, given much higher demand and the resulting higher prices, higher costs relative to brine sources could be covered with a resulting acceptable rate of profit on capital investment. Evans does provide a resource estimate of 2.6Mt contained lithium<sup>10</sup>, which is the figure in A&O's resource column<sup>1</sup>. A final point of contention regarding the average grade of the North Carolina lithium pegmatites is noteworthy. Tahil, referring to Evans' apparent quote of N.C. pegmatites expert Kesler of the USGS, reports an average Li grade of 70 ppm (0.007%). Evans' answer? "The ore in North Carolina normally grades 0.6% Li, definitely not the 70 ppm quoted by Tahil."<sup>11</sup> Evans, shortly before this statement, had indicated that "a typical grade for most pegmatites" is 0.6% lithium content.

Bikita Minerals in Zimbabwe, according to Garrett<sup>19</sup>, has 23Mt of proven ore at an average grade of 1.4%  $\text{Li}_2\text{O}$ , which, doing the math, is equivalent to about 150,000 tonnes of lithium metal. This according to Tahil should not be considered a proven reserve but a resource, since he quotes a USGS reserve figure of 23,000 tonnes. Even with these figures, Tahil leaves the lithium resource and recoverable reserve columns blank in his table 4.2.<sup>33</sup> Would Tahil's omission be due to his belief that lithium carbonate has never been produced using the Bikita ores (spodumene, petalite, lepidolite, eucryptite, amblygonite) or would it be because he is doubtful of future Bikita production since the passing of Zimbabwe's Indigenisation and Empowerment Act which resulted in the eviction of the white management by black "war veterans"? Evans reveals that lithium carbonate had been

produced in Italy and Great Britain with Bikita ores. A&O again fell into error, since they included the 23,000 tonnes (0.023Mt) in their resource column and nothing in the reserve column. This should be rectified. A&O attributed to Evans 0.056Mt lithium as his resource estimate for Bikita. Here again I could find no reference to this or any other figure for Bikita in the Evans documents I had access to. Nevertheless, it seems prudent to trust the figure A&O included in the resource column. The same can be said for the 1Mt resource corresponding to the Russian Federation pegmatites attributed to Evans, the Austrian Koralpa mine pegmatites of 0.1Mt contained lithium resource and the 0.085Mt corresponding to the Brazilian concentrates, all of which are moderate sized pegmatites reported in situ by Evans.<sup>1</sup>

Canadian lithium containing pegmatites: On a large pegmatite straddling the Manitoba-Ontario border, Tantalum Mining Corporation (Tanco) produced tantalum and by-product glass-grade spodumene (5%  $\text{Li}_2\text{O}$ ) at its Bernic Lake, Manitoba property since 1986 but suspended operations in September, 2008.<sup>23</sup> Avalon Ventures Ltd., on its Separation Rapids petalite property near Kenora, Ontario, on the extension of the same pegmatite, as of 2008 was investigating the possibility of recovering a “lithium product suitable for the lithium-ion battery market”<sup>23</sup>. In the case of Tanco, Tahil deemed its low production of contained lithium too small to be a viable resource for lithium carbonate production. He also dismissed Avalon as a resource perspective only destined for the ceramics industry if successful. No reserve and resource figures are given. Evans, on the other hand, mentions that apart from Tanco, for which apparently he did not provide a resource estimate, “other known, but almost certainly unexplored Canadian pegmatites, contain 150,000 tonnes Li”. This figure is 105,000 tonnes short of the 0.255Mt of Li resource in A&O’s Table 8, but, again, I assume these two authors had access to more complete information than I did.

The Lantta/Osterbotten lithium pegmatite, Finland: Curiously, Tahil didn’t include lithium reserve and resource figures in his Table 4.2, although he did derive these data when analyzing the Osterbotten deposit. He declares that the spodumene resource totals 2Mt with a low average grade of only 0.92%  $\text{Li}_2\text{O}$  compared to Greenbushes’ 4%. Doing the math, this results in a lithium content of only 13,000 tonnes, approximately equivalent to 68,000 tonnes (0.068Mt) of  $\text{Li}_2\text{CO}_3$ . With about a 50% recovery rate, this would mean a reserve of barely 34,000 tonnes of lithium carbonate equivalent (Tahil says approximately 35,000 tonnes, 0.035Mt), or about 6,500t Li.<sup>33</sup> A&O wrongly read the figures for Li content, having put a Li resource of 0.68Mt and a Li reserve of 0.35Mt, when they should have inserted a Li resource of 0.013Mt and a Li reserve of 0.0065Mt. Nordic Mining ASA, with a controlling interest in the Finnish mining company Keliber Oy plans a lithium carbonate production of about 6000 tpa, which, according to Tahil, would give the mine a life of probably slightly less than 6 years. Strangely, of all the lithium pegmatite sites that Tahil describes, the only one for which he projects future production of lithium carbonate is this extremely small resource. Apparently Evans reported a lithium resource total of 0.14Mt for Osterbotten, that is if A&O jotted down the correct figure.

The Manolo and Kittolo lithium pegmatites, Zaire, now known as the Democratic Republic of the Congo: This politically, highly unstable country is home to what has been described as “probably the largest hard rock lithium resources in the world”<sup>33</sup>. The political instability and recurrent civil wars of the Congo plus 2,200km of undeveloped transportation infrastructure from the deposit to an ocean port (Lobito in Angola) are what lead Tahil to state that this huge spodumene potential resource is economically

“speculative”.<sup>33</sup> To be sure, many Western mining companies have operations in the unstable Democratic(!) Republic of the Congo (DRC) in spite of the difficulties, and probably, in this sense, Evans dryly retorts to Tahil’s “speculative resource” with an emphatic “hardly”. Things could change for the better in the DRC in years to come and the price trend of lithium and  $\text{Li}_2\text{CO}_3$  according to many analysts will most likely continue upward due to increased demand through the lithium and Li-ion battery markets, both of which factors could result in the eventual exploitation of this remote lithium resource. Evans adds that any project could also potentially recover tin and columbite-tantalite as co-products. He furthermore disputes Tahil’s contention that the amount of lithium in the deposit does not inform one of grade, quality and feasibility of extraction. Of course, feasibility includes the transportation problem, but, aside from this important restriction, 520Mt of ore resource reported by the 1978 National Resource Council were reduced to about 2.3Mt of contained lithium taking into consideration open pit mining, beneficiation and processing losses (a reduction of 25%) and a 0.6% typical lithium content grade for most pegmatites.<sup>11</sup> One could point out that a typical 0.6% grade does not mean that the DRC pegmatite has this high average lithium grade (6,000 ppm). Nevertheless, it seems prudent to accept the NRC’s (and Evans’) resource estimate, which is what A&O did, placing it in their Future Lithium Mining Operations resource column.

The McDermitt Caldera hectorite clays, Oregon/Nevada border: The seven lenses comprising the hectorite clays were initially drilled by Chevron Resources and resulted in a preliminary resource estimate of 2.0Mt of contained lithium, though in one blog Evans mentions 2.3Mt.<sup>12</sup> Years later the Western Uranium Corporation, the following owners of the deposit, apparently were confirming Chevron’s tentative estimate, although their feasibility work involved the detailed drilling of only one of the seven lenses, indicating an estimated lithium reserve content of 162,000 tonnes. Though the cut-off grade for a reserve estimate was placed at 0.275% Li, there are higher grade areas with up to 0.35%.<sup>10-12</sup> Western Lithium, the spin off company of Western Uranium Corporation, was still working on their lithium recovery method and apparently still hadn’t arrived at cost estimates (at least at the time of Evans’ and Tahil’s reports). Even though both authors mention the existence of other hectorite deposits in the United States and Tahil, one in Turkey, the only lithium resource estimate was that of the 2Mt by Evans. This is the figure that A&O added to their possible future lithium mining operations table. Curiously, they erroneously assigned this tonnage to the Hector, California deposit of lithium bearing clays which have never been exploited for their lithium content according to Tahil.<sup>1,33</sup> He concludes that no pilot or commercial extraction of lithium from clays has been done, and, therefore, he excludes these deposits as a resource, much less as a future, potential source of lithium carbonate for the non-automotive battery and automobile industries. Tahil, however, does say that laboratory tests have shown that technically lithium can be extracted from hectorite clays, but only at a high cost, principally because it is a very energy intensive process, as is the extraction of lithium from hard rock ores. It’s interesting to note that Joseph Williams, editor, and James O’Rourke, research specialist, at Madison Avenue Research Group, offer a different vision when stating that “strategic investors would do well to look at shares of companies that have highly prospective hectorite clay or oilfield brines as lithium sources”.<sup>11</sup>

I already mentioned Rio Tinto’s 2004 discovery of a large deposit of the unique mineral Jadarite (in honor of the nearby town Jadar in Serbia) while searching for boron. The 2008 estimated resource of 0.85Mt of contained lithium together with an estimated

13Mt of  $B_2O_3$ \* was only for the lowest of three stacked horizons, so that the company is reasonably optimistic that further exploration could easily double the presently estimated resources.<sup>11,12,13</sup> These are the figures that Evans quotes. The USGS in their 2008 and 2009 lithium reports do not quote a tonnage figure<sup>23</sup>, nor does Tahil, as I already mentioned.<sup>33</sup>

Total Reserves and Resources, 2008: Taking into consideration the changes incorporated into the following table, the sum of Tahil's estimated lithium reserves remains the same as the figure in A&O's Table 1, 4.06Mt, but my revised estimate of Tahil's total resources, 15.6Mt, are significantly lower than A&O's mistaken estimate of 19.18Mt,<sup>1</sup> largely due to the reduction of Salar del Rincón's tonnage from 5.5Mt to 0.5Mt and the incorporation of 1.25Mt in Zhabuye's resource column. Tahil, himself, in his Table 4.2 has a sum total of 15.38Mt of lithium contained resource upon eliminating the 2Mt corresponding to the Dead Sea in Israel, which he certainly didn't consider a viable resource of lithium. Evans in his July, 2008 internet communication<sup>11</sup> arrived at a revised lithium reserve/resource figure of 29.4Mt. In his earlier report (March 29, 2008)<sup>10</sup> the total was 28.4Mt. The revised figure is actually not too far from my estimate of 29.1Mt lithium. If Evans' Smackover oilfield brines lithium content (0.75Mt) is added, his resource total is approximately 29.9, or rounding, 30Mt of contained lithium, which is the rounded figure reported by Evans at the January Santiago conference.<sup>12</sup> As he added, this lithium tonnage corresponds to about 160Mt lithium carbonate equivalent, the primary input for the battery markets and many other uses.

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\* Some of the borate ores are: kernite, colmanite, ulexite, and tincal. Borates are also produced from brines. Kernite is used for making boric acid, tincal for sodium borate production. A few of the end uses for boron compounds in 2010 were: glass and ceramics (78%); soaps, detergents and bleaches (4%); an ingredient in some fertilizers (4%); enamels and glazes (3%), other uses (11%).<sup>65</sup>

## ACTIVE, INACTIVE AND FUTURE LITHIUM MINING OPERATIONS, MILLION TONNES (MT) Li CONTENT, 2008 ESTIMATES

Mine Location(s)	Country	Type of Resource	Source	Li Reserve	Li Resource
Salar de Atacama (Active)	Chile	Brine	Tahil	1	3
Salar de Atacama (Active)	Chile	Brine	Evans		7
Salar del Hombre Muerto (Active)	Argentina	Brine	Tahil	0.375	0.8
Salar del Hombre Muerto (Active)	Argentina	Brine	Evans		0.85
Salar del Rincón (Active)	Argentina	Brine	Tahil	0.25	0.5
Salar del Rincón (Active)	Argentina	Brine	Evans		1.4
Salar del Olaroz (Future)	Argentina	Brine	Tahil	0.16	0.325
Salar del Olaroz (Future)	Argentina	Brine	Evans		0.3
Salar de Uyuni (Future)	Bolivia	Brine	Tahil	0.6	5.5
Salar de Uyuni (Future)	Bolivia	Brine	Evans		5.5
Clayton Valley, Nevada (Active)	U.S.	Brine	Tahil	0.118	0.3
Clayton Valley, Nevada (Active)	U.S.	Brine	Evans		0.04
Zhabuye* (Future)	China	Brine	Tahil	0.75	1.25
Zhabuye* (Future)	China	Brine	Evans		
Qaidam Basin (Future)	China	Brine	Tahil	0.5	1
Qaidam Basin (Future)	China	Brine	Evans		
DXC (Future)	China	Brine	Tahil	0.08	0.16
DXC (Future)	China	Brine	Evans		
Multiple Locations Total	China	Brine	Evans		2.6
Searles Lake, California	U.S.	Brine	Tahil		0.02
Searles Lake, California	U.S.	Brine	Evans		
Great Salt Lake, Utah (Future)	U.S.	Brine	Tahil		0.53
Great Salt Lake, Utah (Future)	U.S.	Brine	Evans		
Salton Sea, California (Future)	U.S.	Geothermal Brine	Tahil		1
Salton Sea, California (Future)	U.S.	Geothermal Brine	Evans		0.316
Smackover Formation, Arkansas	U.S.	Oil Field Brines	Tahil		1

Mine Location(s)	Country	Type of Resource	Source	Li Reserve Year 2008	Li Resource Year 2008
Jiajika (Future)	China	Pegmatites	Tahil		0.006
Multiple Locations, Total (Future)	China	Pegmatites	Evans		0.75
Greenbushes (Active)	Australia	Pegmatites	Tahil		
Greenbushes (Active)	Australia	Pegmatites	Evans	0.223	0.223
Mt. Cattlin (Future)	Australia	Pegmatites	Tahil	0.033	0.066
Mt. Cattlin (Future)	Australia	Pegmatites	Evans		0.02
North Carolina deposits (Inactive)	U.S.	Pegmatites	Tahil		
North Carolina deposits (Inactive)	U.S.	Pegmatites	Evans	0.23	2.6
Bikita (Future)	Zimbabwe	Pegmatites	Tahil	0.023	0.15
Bikita (Future)	Zimbabwe	Pegmatites	Evans		0.056
Multiple Locations (Inactive)	Russia	Pegmatites	Tahil		
Multiple Locations (Inactive)	Russia	Pegmatites	Evans		1
Koralpa (Future)	Austria	Pegmatites	Tahil		
Koralpa (Future)	Austria	Pegmatites	Evans		0.1
Multiple Locations (Active)	Brazil	Pegmatites	Tahil		
Multiple Locations (Active)	Brazil	Pegmatites	Evans		0.085
Tanco (Active)	Canada	Pegmatites	Tahil		
Tanco (Active)	Canada	Pegmatites	Evans		
Multiple Locations (Future)	Canada	Pegmatites	Evans		0.255
Lantta/Osterbotten (Future)	Finland	Pegmatites	Tahil	0.0065	0.013
Lantta/Osterbotten (Future)	Finland	Pegmatites	Evans		0.14
Manolo, Kittolo (Future)**	DemRepCongo	Pegmatites	Tahil		
Manolo, Kittolo (Future)**	DemRepCongo	Pegmatites	Evans		2.3
McDermitt Caldera (Future) OR/NV	U.S.	Hectorite Clay	Tahil		
McDermitt Caldera (Future) OR/NV	U.S.	Hectorite Clay	Evans		2
Rio Tinto's Deposit (Future)	Serbia	Jadarite Mineral	Tahil		
Rio Tinto's Deposit (Future)	Serbia	Jadarite Mineral	Evans		0.85
Total Reserves			Tahil	4.06	
Total Resources			Tahil		15.6
Total Resources			Evans		29.1

\* The USGS says Zabayu Salt Lake.

\*\* The Democratic Republic of Congo was formerly Zaire.

\*\*\*Evans' estimate of 0.75Mt Li in oilfield brines is not included in the table since A&O didn't include it either, but, as a lithium resource, oilfield brines are important.

Using my revised figures, three countries (Chile, Argentina and Bolivia), whose production, as noted, is from brines, enjoy a disproportionate percentage of world lithium resources, about 65% in the case of my revision of Tahil and 52% in the case of Evans. According to the figure assigned to Tahil, Bolivia alone accounts for 35% of world lithium resources, but in the results for Evans, 19%. I agree with Evans that Bolivia is not in a political position to come close to dominating world reserves, although the country will certainly be a major player if it finally succeeds coming on stream with commercially competitive production and distribution. More on this later when I grapple with the geopolitics of lithium.

Evans places great importance on the lithium bearing pegmatite resources of Australia, Canada, China, Democratic Republic of Congo, Russia and the United States, as well as the hectorite clays of the U.S. and the new jadarite mineral deposit in Serbia. Of these countries, Tahil only had very reduced estimates for Mt. Cattlin in Australia and Jiajika in China. Both authors pointed out that a preponderance of resources and reserves are located in 13 countries (Argentina, Australia, Austria, Bolivia, Brazil, Canada, Chile, China, Democratic Republic of Congo, Finland, Russia, US, Zimbabwe).<sup>1</sup> The 14<sup>th</sup> country listed by Evans, Serbia, should also be added.

Just to show how difficult the precise estimation of resources is, during the January, 2009 Santiago, Chile Lithium Supply and Market conference, Chemetall and Foote Mineral Co. presented a relatively low lithium content resource figure (28.0Mt), Sociedad Química y Minera de Chile (SQM) a high estimate (35.7Mt), and Laksic and Tilton, of the Univ. of Chile and Colorado School of Mines respectively (35.0Mt).<sup>12</sup>

Finally, the in situ lithium resources of approximately 30Mt, according to Evans, will likely face a rate of recovery of 50%,<sup>12</sup> which would give us Evans' implicitly estimated recoverable reserves of some 15Mt. As we will see, this would be more than enough for the various markets for lithium, including the exploding lithium and lithium-ion battery markets.

Since the lithium resource estimates for 2008, the perspective of vastly increased lithium demand deriving mostly from the electric vehicle market has greatly stimulated further exploration. The result is an expanded lithium resource base, which geologist R. Keith Evans has carefully monitored. For example, I mentioned before that Talison Minerals' Greenbushes lithium pegmatite resources were increased from Evans' former 0.223Mt lithium content to 1.5Mt<sup>12</sup>, but later apparently reduced to 1Mt<sup>13</sup>. Evans states that the reserves in the Salar de Atacama in Chile "have been more than tripled" and that this salar's lowest grades are higher than the highest grades in the Argentine salares.<sup>15</sup> The Salar de Uyuni resource estimate has jumped from 5.5Mt Li to the revised 8.9Mt. The Salton Sea KGRA (Known Geothermal Resource Area) has an updated resource estimate of about 2Mt Li<sup>13</sup>, although Evans only included an increase from 0.316Mt to 1.0Mt.<sup>15</sup> These examples and others meant that at the second lithium conference in Las Vegas (January, 2010), again organized by Industrial Minerals, Evans' most recent resource estimate reflects the intensive exploration activity of numerous mining companies, large and small: 34.5Mt Li. He assigns the following quantities of contained lithium in millions of tonnes to the different geologic source types: pegmatities (8.9Mt), continental brines (20.9Mt), geothermal brines (1.0Mt), oilfield brines (0.7Mt), hectorite clays (2.0Mt), and jadarite (0.85Mt). Unsurprisingly as the reader can see, the continental brines predominate with close to 61% of the total, followed by the lithium bearing pegmatites (26%). Of the total 34.5Mt Li, Evans adds that current lithium chemical producers accounted for about 7.8Mt

as of January, 2010; advanced new projects an estimated 7.2Mt; and “pipeline” projects, i.e. less advanced project exploration and development, among which are pegmatites, brines, hectorite clays and the mineral jadarite.<sup>15</sup> It’s important to again note that “apart from the pegmatite tonnages in the (NRC) 1975 report all other tonnages are *in situ*”<sup>14</sup>, including pegmatites not listed in the report and the different lithium brines, and, furthermore, “all the projects are expected to be viable and capable of producing battery grade lithium carbonate”<sup>15</sup>. That all the projects are “expected to be viable” is one thing. That all will be economically viable will be seen in the future. The lithium consulting company TRU Group believes that “existing lithium plants will continue to dominate the market through 2020 and that pipeline projects will account for less than one-fifth of production by 2017”.<sup>50</sup>

The USGS, also reflecting the booming exploration activity in many countries, significantly increased its lithium resource estimates from about 14Mt Li in 2008 (0.76Mt in the U.S. and more than 13Mt in other countries) to approximately 25.5Mt Li in 2009 and 33Mt in 2010 (USGS: mineral commodity surveys, 2009, 2010, 2011).<sup>65</sup> Evans’ total for the USGS in 2009 is 9.9Mt Li<sup>15</sup>, which doesn’t correspond to the January, 2010 pdf file I downloaded. At any rate, the latest USGS resource estimate, as Evans says, has increased dramatically.

#### IV. USES AND DEMAND

The uses and demand for lithium and lithium compounds obviously are intimately tied to the production and supply response of the companies engaged in this activity, prices signaling to both consumers and producers what actions they should take. From this perspective, demand, supply and price variations should, in theory, be dealt with simultaneously. Nevertheless, for clarity of exposition in this section IV, I shall generally limit the discussion only to the demand side of the equation, leaving the supply side for the following section and prices afterwards. Why prices afterwards? Because lithium and its compounds are not transacted on commodity exchanges, such as copper. There is no spot pricing. Contracts are generally proprietary between buyer and seller. This results in difficulties to find adequate price quotes, much less useful price series.

USES\*: Firstly, it is important to note that lithium carbonate ( $\text{Li}_2\text{CO}_3$ ) is the most important lithium compound produced from the processing of brine and ore deposits and that most other lithium compounds require lithium carbonate as a feedstock for further processing. With this in mind, the ceramics and glass industries have been the major consumers of lithium carbonate and lithium mineral concentrates, with the exception of 2007-08. Although there are substitutes for these inputs, they have the property of lowering the process melting points and viscosity of the mix (thus saving energy), reducing the coefficient of thermal expansion (important for glass and ceramics, for example, in pyroceramic thermal resistant cookware), and avoiding the use of more toxic substitute compounds as inputs. Regarding ore concentrates, low iron spodumene and petalite can be used directly as a source of both lithium and alumina, another important ingredient, in the production of container and bottle glass. The lithium content from carbonate and high grade ore concentrates leads to lighter weight and thinner walled products, an additional saving for manufacturers.

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\* The major source of uses in this paper is from diverse USGS lithium summary publications.

From 1994 to 2000, the second most important use of lithium compounds in the U.S. was in the primary production of aluminum (aluminum smelters). Since 2000, primary aluminum production has decreased in the United States because of high energy costs, and, therefore, the input of lithium has shrunk in this industry. The use of lithium carbonate lowers the melting point of the cryolite (sodium aluminum fluoride,  $\text{Na}_3\text{AlF}_6$ ) bath, thus lowering the operating temperature of the process and, at the same time, increasing the electrical conductivity of the bath (again an energy saver). A benefit for the environment from the addition of lithium carbonate is the reduction of fluorine emissions.

Lubricating greases made from lithium hydroxide monohydrate are another important end use of lithium due to their retaining the lubricating property over wide temperature ranges, as well as their resistance to water, oxidation and hardening. These greases have many applications in the automotive, aircraft and marine industries.

Catalysts made from lithium compounds also are an important end use of lithium. The compound N-butyllithium is used as a catalyst to make synthetic rubber that resists abrasion and thermoplastic rubber requiring no vulcanization. Other lithium compound catalysts are used to make plastics, for example, polyethylene, and drug manufacturers use metallic lithium and lithium compounds to produce a wide variety of drugs and other products (vitamin A, some steroids, anti-cholesterol agents, an analgesic, antihistamines, tranquilizers, sleep inducers, contraceptives, and even pharmaceutical grade lithium carbonate for manic-depressive psychosis)<sup>40</sup>.

At least from 2004 the second major world use of lithium has been the battery markets, both chargeable (secondary) and non-rechargeable (primary) batteries, and for apparently two years, 2007-08, the battery markets were ranked number one. As we shall later see, lithium's natural properties make it one of the most attractive elements for battery production. Non-rechargeable lithium batteries have been commercially available for about 30 years and are now used in cameras, electronic games, microcomputers, small appliances, toys, watches, hearing aids, and many military uses, among numerous other applications. Continuously improving rechargeable battery configurations have been and are being introduced for the rapidly changing requirements of electronic products such as cell phones, laptop computers and video cameras.

Rechargeable lithium-ion batteries\* are increasingly being used in heavy duty power tools and, of course, a major market is developing for lithium-ion powered hybrid electric vehicles (HEVs), plug-in hybrid electric vehicles (PHEVs), and on a lesser scale pure electric vehicles, sometimes called battery electric vehicles (BEVs).

In some countries aircraft manufacturers use lithium-aluminum alloys to reduce up to 10% of the weight of wing and fuselage skin or structural members of planes (an important fuel saver over the life span of aircraft), though these alloys face competition from so-called composite materials containing boron, graphite or polymer fibers, which have reduced the demand for lithium compounds in this industry.

Many other industries use small amounts of lithium compounds. Lithium chloride (LiCl) and lithium bromide (LiBr) are used in industrial air-conditioning and dehumidification systems as well as in producing certain textiles. Lithium hypochlorite is used in sanitizers for swimming pools, commercial glassware, public restrooms and dry bleaches for commercial laundries. To remove impurities from copper and bronze, metallic lithium serves as a scavenger. Anhydrous LiCl is used in fluxes for hard-to-weld aluminum, steel alloys and other metals. To help prevent or reduce the deterioration of concrete, lithium compounds are increasingly being used as an additive, plus being added to mortars and cement to accelerate setting and hardening. An interesting development is that advanced by Japanese researchers. Lithium silicate was found to absorb ten times more CO<sub>2</sub> from flue gases than other carbon dioxide absorbents so that its use in power plants and other CO<sub>2</sub> emitters is promising.

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\* Because certain uses of lithium batteries (particularly larger batteries for transportation, laptop computers, heavy duty power tools, etc.) require major safety assurances, the use of primary lithium batteries, in which the anode is made from metallic lithium, poses safety issues. This danger resulted in the development of lithium-ion batteries. A Li-ion battery is a family of rechargeable battery types in which lithium ions Li<sup>+</sup> carry the current from the negative electrode (anode) to the positive electrode (cathode) during discharge, through a non-aqueous electrolyte. During charging, an external electrical power source applies a higher voltage than that produced by the battery, forcing the current to pass in the reverse direction. The lithium ions then migrate from the positive to the negative electrode. Unlike metallic lithium primary (non-chargeable) batteries which are disposable, rechargeable lithium-ion electrochemical cells use a porous intercalated lithium compound as the electrode material. Commercially, the most popular anode material is graphite, while the cathode is generally one of three compounds: an oxide such as lithium cobalt oxide (LiCoO<sub>x</sub>), a polyanion such as Lithium iron phosphate (LiFePO<sub>4</sub>), or a spinel such as lithium manganese oxide. The non-aqueous electrolyte, is typically a mixture of organic carbonates such as ethylene carbonate and complexes of lithium ions such as lithium hexafluorophosphate (LiPF<sub>6</sub>). Recalling that pure lithium is highly reactive with water, the three components (anode, cathode and non-aqueous electrolyte) are sealed in a water-proof battery pack. Lithium ion batteries are still very expensive, much more than nickel cadmium batteries (NiCd) for example, but they function over a wider temperature range and have a higher specific energy (Wh/kg), plus being able to be smaller and lighter, characteristics which make them desirable for electric vehicles.<sup>73</sup>

### Uses of Lithium Minerals (Concentrates) and Lithium Chemicals, % of Total

USE	1994 <sup>a,b</sup> to 1999	2000 <sup>c,d</sup>	2004 <sup>c,e</sup> to 2006 <sup>f</sup>	2006 <sup>c,g</sup>	2007 <sup>c,f</sup>	2007 <sup>c,g</sup> to 2008 <sup>c,f</sup>	2008 <sup>c,h</sup>	2009 <sup>c,f</sup>	2009 <sup>c,g</sup>	2009 <sup>c,k</sup>	2009 <sup>c,h</sup> to 2010 <sup>c,f</sup>	2010 <sup>31</sup>
Ceramics and Glass	20	50	21	21	20	18	37	31	30	20	31	27.5
Primary Aluminum Production (Smelters)	18		6	5	6	4	7	3	3	6	6	6.0
Synthetic Rubber and Pharmaceuticals (and polymers)	13	9	9*	9*	9*	7*	5***			5	6***	7.0*
Continuous Casting						3	5	4			4	
Chemical Manufacturing (Processing)	13					3			5 <sup>iv</sup>			
Miscellaneous Chemicals	12											
Lubricants (Lubricating Greases)	11	18	16	17	16	12	11	10	10	13	9	11.5
Batteries	7	9	19	20	20	25	20	23	21	29	23	22.5
Air Treatment (Air Conditioning)	4		8	7	8	6	5	5	5	8	6	5.5
Other Uses	2	14	21	20**	21**	22**	10	24	26	19 <sup>v</sup>	15	20.0

- a) U.S. uses, USGS source data  
b) Cyprus Minerals Co. 1992, annual report 1993  
c) World consumption (global end use markets)  
d) Schmitt, Bill, 2000, Chemical Week, v.162, no. 34  
e) SQM (Sociedad Minera y Química de Chile, S.A.), 2005  
f) USGS, lithimcs07.pdf, mcs-2008-lithi.pdf, mcs-2009-lithi.pdf, myb1-2007-lithi.pdf, mcs-2010-lithi.pdf  
g) SQM, 2006, 2008  
h) Roskill Information Services, in USGS myb1-2008-lithi.pdf, myb1-2009-lithi.pdf  
k) FMC, cited in index.php.htm  
\* Pharmaceuticals and Polymers  
\*\* Alloys, construction, dyestuffs, industrial bleach and sanitation, pool chemicals, specialty inorganics  
\*\*\* Rubber and thermoplastics plus pharmaceuticals  
iv Metallurgical  
v Includes construction 2%.

From 1994 to 1999, the data are only for U.S. uses. From 2000 to 2010, world information is given. The ceramics and glass industries plus primary aluminum production were the major U.S. users of lithium during the 1994-1999 period. Their combined world consumption of lithium was approximately 50% of the total during 2000. Battery use of lithium was quite low (7% from 1994 to 1999 in the U.S. and 9% of the world total in 2000), but grew rapidly from 2004 onward to 2010, possibly reaching number one in the world ranking in 2007-2008 with about 25% of the total lithium consumption, as already mentioned. The battery end use of lithium for 2008 differs between the USGS estimate and Roskill's estimate, though not overly widely (25% and 20% respectively). If the correct estimate for 2008 is 25%, relative lithium use in batteries apparently descended slightly up to 2010 according to three sources (SQM, Roskill and the USGS). FMC (Foote Mineral Co.) presented an outlier estimate for 2009 of 20% for ceramics and glass and a high battery estimate for lithium use of 29%, which, if correct, would mean that battery use of lithium could possibly still be ranked first. World aluminum smelter use of lithium has tended to be quite low since 1994-1999 and 2000 relative to total consumption, particularly in 2009 owing to the economic recession in rich industrial countries when this lithium end use fell to about 3% of total world lithium consumption according to the USGS and SQM estimates, though the Roskill estimate is 6%. Unfortunately, estimates differ widely, as also can be seen in 2008 for ceramics and glass. Whereas the USGS figure for lithium end use in these industries is 18% of the world total, the Roskill estimate is 37%.

DEMAND ANALYSIS: Throughout the 1990s the demand of lithium and its compounds was largely determined by the health of the ceramics and glass industry, the aluminum industry and, of course, the economic outlook in general. Demand for lithium compounds and minerals (spodumene, petalite, lepidolite and others) for use in ceramics and glass grew at a modest rate. Even as early as 1994 it was stated that the lithium battery market's success would be largely tied to the still uncertain future success of electric vehicles as a mass mode of transportation and to whether or not their power would be provided by some kind of lithium battery. By 1996-97 the panorama had changed regarding lithium-ion batteries, i.e. those that use lithium in forms other than metallic lithium. The greatest future potential for lithium demand now appeared to lie with the battery market. In 1996 Li-ion battery sales were greater than the then oft used nickel cadmium battery in Japan for the first time, particularly due to the explosive cell phone, laptop computer and other consumer electronic markets. Year 1998 marked the Nissan Motor Corporation's debut in the fledging U.S. EV market at the Los Angeles Auto Show, with a lithium-ion powered 4-passenger mini van, developed jointly with Sony Corp. This EV was the first of any auto manufacturer to use lithium-ion batteries. Most used either NiCd or nickel metal hydride (NiMH) batteries. Though the first rechargeable batteries (lithium-ion and lithium polymer batteries) were introduced in 1993 with low sales, in 1998 this market had grown to about \$3 billion, and at the time was projected to increase to some \$6 billion by 2005, according to Pacific Lithium Ltd. (2000).<sup>40</sup> One thing is the value of the batteries sold; another is the value of the lithium materials used in these batteries. For both rechargeable and non-rechargeable lithium batteries, the estimated sales of lithium materials was only a modest \$111 million in 1997 but with a preliminary forecast of 16% yearly growth through 2008.<sup>40</sup> The lithium battery market was expected to burgeon.

In a USGS 2003 report<sup>41</sup>, global rechargeable and non-rechargeable lithium battery sales volumes were increasing yearly between 25% and 30%, while the value growth of sales was less, 12% to 15% per year, which indicates that the price per battery on average was falling. The world market for rechargeable lithium-ion and lithium polymer\* batteries had reached approximately \$3.5 billion in 2003, \$4 billion in 2005, \$5.2 billion in 2007, and about \$7.4 billion in 2008, corresponding to growth rates above 20% per year. Nevertheless, during these years most car manufacturers were still using nickel metal hydride and NiCd batteries, though the lithium-ion battery configuration would improve sufficiently to displace NiMH as the preferred choice, thus increasing the demand for lithium. For example, the use of nanotechnology\*\* has permitted the development of fast recharging lithium-ion batteries, apparently more or less equivalent to the time it takes to fill the gas tank of an internal combustion driven car. Another example of performance improvements is that of a two fold increase in lithium-ion battery specific energy (Wh/kg) by 2006 in comparison to the 1991 level when this type of battery was first introduced. Furthermore, pure battery electric vehicles (BEVs) had lost some favor among many of the major carmakers, the strategy turning ever more toward hybrid electric vehicles (HEVs) containing a small internal combustion engine and a battery powered electric motor, as well as plug-in hybrids (PHEVs). The PHEVs would be larger than those used in HEVs since

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\* Because lithium polymer batteries can be constructed in differing shapes, they have become popular with many electronic equipment manufacturers, although most lithium batteries sold are of the lithium-ion variety.

\*\* A nanometer is one billionth of a meter. Nanotechnology roughly has applications between 1 and 100 nanometers.

they would have a longer electric driving range. Besides research which has increased the output power and decreased the recharge time of lithium-ion batteries, much effort has gone into trying to improve their stability and lifespan. These attributes would boost EV sales too and eventually impinge on the demand for lithium. Other markets were also growing, although at lower rates. In the USGS 2008 lithium report<sup>23</sup>, according to Roskill Information Services, the past 8 year average yearly growth rates of lithium consumed in pharmaceuticals, continuous casting and lubricants were 17%, 8% and 6% respectively. Nevertheless, most analysts agree that the demand for lithium will increase most rapidly in the lithium battery market, where in 2006 two thirds of worldwide rechargeable battery sales were lithium based, including, for example, 90% of laptop computers and 60% of cell phones.<sup>41</sup> By 2008, in a report by Rockwood Holdings, Inc., worldwide lithium based rechargeable battery sales had reached 70% of the total, and in the portable rechargeable battery market, lithium-ion batteries represented about 75% of the total. In the heavy-duty power tool market, demand for larger lithium batteries was projected to grow 15 times from 2006 to 2012, from a 2006 base in which about 22% of all heavy-duty battery powered tools used lithium-ion batteries.<sup>23</sup>

Total U.S. lithium consumption declined in 2008 and 2009 in most end uses because of the country's recession. Inputs of lithium for primary aluminum production dropped as this sector shuttered its smelters due to the price decline of aluminum and high electricity prices, a situation which continued in 2009. However, worldwide lithium consumption rose due to the fast growing Chinese and Indian markets and increased consumption by foreign battery manufacturers, particularly in Asia where most lithium batteries are manufactured (of lithium-ion batteries, 39% in Japan, 36% in China, and 20% in South Korea).<sup>23</sup> It's noteworthy that major carmakers as early as 2008 began partnering with Japanese lithium-ion battery manufacturers to build hybrid battery plants. Perhaps as a partial answer to this Asian concentration of lithium battery production and within the context of the economic slowdown in the U.S., President Obama's 2009 American Recovery and Reinvestment Act launched an element of industrial policy, making available \$2.4 billion in grants to be administered by the Department of Energy (DOE) for the purpose of developing a major U.S. battery and electric drive component manufacturing capacity related to the electric vehicle industry. Apparently during 2009 \$1.5 billion had been granted to suppliers of lithium materials, lithium battery producers and also a lithium battery recycling company (Toxco Inc.). The total \$2.4 billion fund complements DOE's 2008 \$25 billion of direct loan funds under the auspices of the Advanced Technology Vehicles Manufacturing Incentive Program. Under this program, Tesla Motors of California, a fully electric BEV manufacturer, was loaned \$465 million to build lithium-ion battery, electric motor and electric drive train assembly plants. Nissan of North America received a \$1.6 billion loan to convert to electric car production and manufacture Li-ion battery packs in its Tennessee auto plants. Fisker Automotive Inc. was loaned \$528 million leading to the production of PHEVs powered by lithium-ion batteries.<sup>23</sup> HEVs, PHEVs and pure EVs in small numbers with lithium-ion batteries were marketed by BYD of China, Daimler of Germany and Tesla in 2009, while the big majors (GMC, Hyundai, Mitsubishi, Nissan, Toyota and Volkswagen) in 2009 were announcing the arrival of these 3 types of electric vehicles for 2010.<sup>23</sup> These examples serve to emphasize the commitment of the companies and the U.S. government to the use of lithium materials in the auto industry, which potentially will increase the demand for lithium significantly.

In spite of the economic downturn of the latter half of 2008 and continuing in 2009, worldwide sales of lithium-ion rechargeable batteries in 2009 were estimated at \$7.7 billion, up from the before mentioned sales of \$7.4 billion corresponding to 2008, a modest increment of 4%, well below the more than 20% annual growth of former years. A 2009 report by Crédit Suisse forecasted a 13% yearly growth rate of Li-ion battery sales. Because of uncertainties regarding the economic health of the rich industrialized world, it will only be seen if the projected 2013 sales figure of \$13 billion will be attained. Pike Research estimated that global sales of lithium-ion batteries for the transportation industry may grow to \$8 billion by 2015, up from the figure of \$876 million in 2010. Pike also forecasted important growth in the use of large Li-ion storage batteries for electricity grids and other utility purposes (\$8 billion sales for 2018). The uncertainty inherent to these forecasts also applies to Roskill's projected total lithium consumption for 2013 of 27,600 metric tonnes, a 48% increase from their estimate of a little less than 18,700 tonnes for 2009.<sup>23</sup> These optimistic forecasts, however, belie the impact of the global economy's 2008-09 crisis on the major producers of lithium concentrates and lithium containing brines, whose sales were reportedly down by between 15 and 42% depending on the particular producer.<sup>65</sup>

Because of the growing importance of electric vehicle production and the increasing use of lithium-ion batteries to power these vehicles, the exercise of estimating the global demand of lithium for this purpose becomes indispensable, so as to be able to judge how much ongoing lithium production will be necessary and, additionally, to determine if reserves and resources can satisfy accumulating vehicle demand, at the same time satisfying non-automotive demand. To launch this exercise, I'll begin with Tahil's effort to quantify lithium carbonate demand by the auto industry, interspersing his analysis with Evans' comments, some by Abell and Openheimer, others by important producers, and my own judgment. First of all, a battery's capacity is measured in kilowatt hours (kWh), and in rechargeable lithium-ion batteries, a certain amount of lithium is used per kWh. However, since  $\text{Li}_2\text{CO}_3$  is the raw material used to convert to lithium compounds necessary for the manufacture of these batteries, typically the lithium carbonate equivalent (LCE) per kWh is the measure employed, i.e., kgs  $\text{Li}_2\text{CO}_3/\text{kWh}$ .<sup>\*</sup> Tahil, without explaining why, uses 1.4kgs/kWh.<sup>54</sup> It's true that a common estimate is 3.1 pounds/kWh, equivalent to the 1.4 kgs used by Tahil, which is also apparently the calculation used by the Argonne National Laboratory.<sup>24</sup> Evans justifies the use of 0.6 kg carbonate per kWh saying that the three principal producers (SQM, Chemetall and FMC) all used the same amount for their demand estimates for the future and that most likely they are in frequent contact with both current and future customers regarding the technical aspects of the batteries. He makes clear that estimating lithium demand is very difficult and, therefore, the results vary significantly depending on the assumptions regarding the annual world vehicle production over time, the projected EV penetration, the type of EV (whether HEV, PHEV or fully electric BEV, which determines the size of the battery), and the percentage of EVs that are lithium-ion battery powered, besides the aforementioned kilograms of  $\text{Li}_2\text{CO}_3/\text{kWh}$ . Additionally, the estimates can vary because of different possible lithium-ion chemistries.<sup>13,14</sup>

Tahil, in his 2007 paper<sup>54</sup>, presented an extreme demand scenario in which he estimates LCE demand for the world automobile stock of 900 million vehicles, using 1.4 kgs  $\text{Li}_2\text{CO}_3$

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\* The lithium carbonate equivalent of 1 unit of lithium is approximately 5.32 units of  $\text{Li}_2\text{CO}_3$ , based on the atomic weights of the respective elements (Li, C, O). This is the figure used by Evans, but, curiously, Tahil uses 5.28 as the equivalent.

per kWh, and a battery size equivalent to 5kWh/vehicle, which results in 6.3Mt of LCE.\*\* This would represent about 18% of his estimated 33.55 Mt of economically viable  $\text{Li}_2\text{CO}_3$  reserves for 2007. Tahil then doubles the battery size to 10kWh, considering this more realistic, which means the percentage of LCE demand for the auto fleet jumps to 36% of reserves. He also states that a 10kWh battery may be too small, which certainly is true for some vehicles. For example, Abell and Openheimer quote a battery capacity of 16kWh for GM's PHEV Volt.<sup>1</sup> The problem with these estimates is that not all the automobile fleet can be nor will be converted rapidly into EVs. The number of cars Tahil used is even subject to doubt. The International Monetary Fund (IMF) estimated the world stock of cars in 2009 to be 700 million<sup>13</sup>. The LCE reserve estimate, as we have seen, is also questionable. It should be remembered that Tahil excluded the pegmatite lithium minerals as unsuitable for the production of  $\text{Li}_2\text{CO}_3$  for use in lithium batteries. He only considered the lithium brines as a viable source of lithium destined for use in lithium-ion batteries. Evans' estimated economic resources and reserves of LCE, as we saw, are much higher, in part because he does correctly include important lithium containing pegmatite deposits so that with only a fraction of lithium carbonate production used in the auto industry, according to him there will be enough to avoid an undersupply for the various industries demanding lithium. In 2010, Evans places total reserves and resources at about 25Mt contained lithium, not including Bolivia's Salar de Uyuni vast resources due to political uncertainties, which translates into 133Mt of  $\text{Li}_2\text{CO}_3$  equivalent. At a 50% recovery rate, this would yield about 66.5Mt, twice as much as Tahil's figure. Then, too, which is closer to the truth, the 1.4 kgs  $\text{Li}_2\text{CO}_3$ /kWh or the 0.6 kg accepted by Evans? Strangely, even Evans at times in his own estimates has used 1 kg/kWh as an average, as we shall see in a couple of examples. The truth of the matter is that I don't know. However, since Tahil doesn't justify his figure and Evans does, I shall accept that the amount of LCE per kWh lies between 0.6 kg and 1 kg. But, returning to the extreme demand scenario postulated by Tahil, the most pertinent critique is the time frame leading to an increasing percentage of EVs in the world stock of vehicles with lithium-ion batteries. As Evans says, there will not be a "wholesale abandonment of the existing motor vehicle fleet"<sup>11</sup>. A preponderant share of older vehicles will continue to run on gasoline or diesel powered engines. Some will be powered by bio-fuels or natural gas. Others will be powered by alternative battery chemistries and fuel cell systems. Ongoing research is being done on hydrogen powered engines, zinc-air and zebra (NaNiCl) batteries, and capacitor technology. One could conclude that Tahil's extreme scenario is alarmist. But, let's see some further calculations by Tahil before turning to Evans and other sources of demand and, afterwards, production.

Tahil's estimate of global lithium carbonate production for 2006 was 75,000 tonnes and for 2010 he projected it to be about 150,000 tonnes.<sup>54</sup> Of the 75,000t, Tahil accepted the end use of batteries to be 20%, so that this sector would consume about 15,000t. To produce one million PHEVs would require about 14,000t of  $\text{Li}_2\text{CO}_3$ , just about the entire amount available for all lithium battery production, including the fast growing laptop and cell phone market demand (estimated to be growing by 20% per annum).\* Tahil also says that if the entire supply of the estimated production of 150,000 tonnes of LCE corresponding to 2010 were used only for the production of PHEVs, that would only be

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\*\* (900,000,000 vehicles) X (1.4 kgs  $\text{Li}_2\text{CO}_3$ /kWh) X (5kWh/vehicle) = approximately 6.3Mt  $\text{Li}_2\text{CO}_3$ .

\* (1,000,000 PHEVs X 1.4kg  $\text{Li}_2\text{CO}_3$ /kWh X 10kWh/PHEV) / (1000kg/tonne) = approximately 14,000 tonnes of LCE.

sufficient for about 5 million of these vehicles. Curiously, this means that Tahil didn't assume the use of a 10kWh battery but instead one of 20kWh.\*\* It's important to note that Tahil compares this to an estimated global yearly production of 60 million automobiles, far above the 5M PHEVs. Of course the 150,000 tons of LCE could not be used only for the auto industry, excluding all the other important end uses, but the point is that Tahil wants to show how lithium carbonate production will never be enough to convert the car fleet to lithium-ion power. In his extreme scenario of wholesale conversion, things are made worse when Tahil factors in carbonate demand for commercial vehicles, for which much larger Li-ion batteries would be required. One of his examples is to show how many tonnes of lithium carbonate would be required for the yearly global sales of 10 million commercial trucks if a Li-ion battery of a modest 100kgs/kWh were required. These 10M trucks would consume about 1.4Mt of  $\text{Li}_2\text{CO}_3$ . Add onto this tonnage the 840,000 tonnes\*\*\* required for the annual production of the 60 million autos (using Tahil's 1.4 kgs/kWh and 10kWh/car) and the world would consume many multiples of the entire 150,000 tonnes of  $\text{Li}_2\text{CO}_3$  production that Tahil forecast for 2010. Worst yet, Tahil mentions that the largest trucks would require batteries of greater power provided with 200kgs/kWh or more. Li-ion batteries beyond 200kgs/kWh would be weight prohibitive according to Tahil and, thus, would require "another battery technology with much higher energy density"<sup>54</sup>, i.e. specific energy (Wh/kg), so that an acceptable battery weight with sufficient levels of energy storage can be achieved for heavy trucks. Here again, the entire fleet of cars and trucks, both new and old, will not be powered rapidly by only Li-ion batteries.

In Tahil's Meridian International Research (MIR) 2008 paper, there is an interesting presentation of several production-consumption forecast scenarios for 2010, 2015 and 2020.<sup>33</sup> I won't rehash figures for 2010, except to say that he reduced his  $\text{Li}_2\text{CO}_3$  equivalent production forecast to 130,000 tonnes from the former 150,000 tonnes, which would cast an even more negative light on LCE availability for consumption. His optimum high scenario forecast of  $\text{Li}_2\text{CO}_3$  production for 2015 is a possible 234,000 tonnes (Table 4, p.40), while his high scenario non-auto demand is 203,000t (Table 5, p.43), leaving 31,000t of chemical grade  $\text{Li}_2\text{CO}_3$  available for the auto industry, though Tahil rounds this to an even 30,000t. What does the optimum high scenario production mean for Tahil? Well, chemical grade  $\text{Li}_2\text{CO}_3$  must be purified further to reach the battery grade purity requirement of 99.95%, but Tahil is assuming that battery grade processing capacity rises easily and he is abstracting from the details of processing losses. Additionally, the 2015 production figure includes 15,000t from the Salar de Uyuni which hasn't as yet produced any commercially available LCE, as well as Chinese production which may or may not be available for the auto sector in China, but may be consumed domestically and not exported in significant quantities, if at all. With the above assumptions in place, the 30,000t of  $\text{Li}_2\text{CO}_3$  would suffice for the production of about 1.3 million GM type Volts.\* In addition to other doubts, why Tahil would assume that Volt class PHEVs and not some combination of HEVs and PHEVs would be the choice is difficult to say. Finally, if the optimum production scenario is not reached, Tahil predicts that possibly only 170,000t would be available in 2015 and 220,000t in 2020, but he doesn't present a justification for these

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\*\*  $(150,000,000\text{kgs } \text{Li}_2\text{CO}_3) / (1.4\text{kgs } \text{Li}_2\text{CO}_3/\text{kWh} \times 20\text{kWh}/\text{PHEV}) = 5,350,000$  PHEVs, not far from 5M

\*\*\* Tahil calculated about 700,000 tonnes. How he did it, I don't know, since he didn't give the reader all the variable data.

\*  $(30,000,000 \text{ kg } \text{Li}_2\text{CO}_3) / (1.4\text{kg } \text{Li}_2\text{CO}_3/\text{kWh} \times 16\text{kWh}/\text{Volt}) = 1,339,286$  Volts, i.e. about 1.3 million

figures. For 2020, Tahil's high production and high non-auto demand scenario are 308,000 and 263,000 tonnes of  $\text{Li}_2\text{CO}_3$ , respectively, the difference (45,000t) being available for autos. Again, if these autos were PHEV Volt types (battery capacity: 16kWh/Volt), about 2 million Volts could be produced, a total drastically short of the projected total number of autos to be produced in 2020.

The high production scenario combined with high non-auto demand is not Tahil's denominated "best case combination". This case combines optimum high production with the low non-auto demand scenario. This latter demand is assumed to grow at only about 4% per year during the 2007-2020 period. This would leave some 110,000t of  $\text{Li}_2\text{CO}_3$  for the auto sector in 2015 according to Tahil, which means that the low non-automotive demand would be 124,000t (234,000 – 110,000). The 110,000t would be sufficient for about 5M Volt type PHEVs in 2015.\*\* The equivalent exercise for an estimated 160,000t of  $\text{Li}_2\text{CO}_3$  available for the global auto industry in 2020 results in about 7.5M Volt type vehicles.

The low production scenario (170,000t for 2015 and 220,000t for 2020), where the principal restriction entails more time required to develop additional resources, combined with the slow 4% growth of non-automotive demand (120,000t and 140,000t for 2015 and 2020 respectively) means that 50,000t and 80,000t of  $\text{Li}_2\text{CO}_3$  are available for the two years. Doing the math results in the potential production of about 2.2M Volt class electric vehicles for 2015 and 3.6M for 2020, as Tahil indicates.<sup>33</sup>

In the high production and high non-automotive demand scenarios, Tahil abstracted from the processing losses involved in converting from chemical grade to battery grade lithium carbonate, the former being the primary raw material produced from brines and ore concentrates. He states that possibly only about 70% of the chemical grade  $\text{Li}_2\text{CO}_3$  will end up as high purity battery  $\text{Li}_2\text{CO}_3$ . In other words, the processing loss is 30%, which, according to Tahil, means that the lithium carbonate tonnage available for batteries should, in a more prudent estimate, be reduced by 30%. If what Tahil says is true, the price difference between chemical grade and battery grade  $\text{Li}_2\text{CO}_3$  should be considerable. Evans, however, confirms that the price difference between the high grade and low grade material is only in the range of 5 to 10%, which is an indirect way of stating that processing losses could not be as high as 30%.<sup>14</sup>

There is also the issue of recycling. The less lithium compounds that have to be dug out of the ground or processed from brines because of a greater recycling volume, the more easily becomes the ability to meet future demand. Tahil seems to be pessimistic about the recycling of lithium batteries for at least the near future. He does cite the European Union directive for member countries to recycle 45% of portable lithium equipment batteries by 2016, but, along with other analysts, he doubts this goal will be met. As of 2008, he states that the U.S. had emitted no directive in this regard.<sup>33</sup> In the case of the U.S., it was already mentioned that there is at least one lithium battery recycling company now operating, Toxco, and that the U.S. Department of Energy has awarded this company a grant to build a plant in the U.S. in addition to its existing plant in Canada. Abell and Oppenheimer

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\*\* Just to see that non-automotive  $\text{Li}_2\text{CO}_3$  growth from 2007 to 2015 is fairly close to 4%:  
 $124,000 = 85000(1 + x)^8$  Therefore,  $x = (124/85)^{1/8} - 1 = 0.0483$  or not far from Tahil's 4%, though closer to 5%. From this:

$(110,000,000 \text{ kg } \text{Li}_2\text{CO}_3) / (1.4 \text{ kg } \text{Li}_2\text{CO}_3/\text{kWh} \times 16 \text{ kWh/Volt}) = 4,910,714$  i.e. about 5M Volt class autos

\* As a matter of fact, Evans erroneously says Tahil had reported a 70% loss. Furthermore he states in his December 10<sup>th</sup>, 2010 blog that "prices vary but battery grade carbonate is typically between 10% and 15% higher".<sup>15</sup>

mention that the DOE has been working on the issue of recycling lithium-ion batteries since the 1990s and that GM, Ford and Chrysler have worked together to fund a R&D facility, On to Technology, for the recycling of NiMH and Li-ion batteries. These authors see no reason why large scale recycling of lithium batteries won't happen, like the present 95% recycling of U.S. lead-acid vehicle batteries, although they recognize that this will only occur when mass quantities of EV batteries are produced. Joseph Williams and James O'Rourke of Madison Avenue Research Group have written that although such a program of lithium battery recycling has not yet emerged in an important way, it surely will since metals are "not used up" but can be used and reused for a long time.<sup>11</sup> Evans puts forward the idea concisely by stressing that "lithium is not consumed in the process of storing energy" and that "when large scale recycling of lithium batteries kicks in ten years or so after initial large scale usage, primary lithium production could fall significantly."<sup>13,15</sup> This was also a warning to the Bolivian government to "lay out a red carpet for potential partners if they can help accelerate evaluation and possible development" of the Salar de Uyuni instead of "continuously preaching about potential exploitation".

It's worth recalling what Tahil said in MIR's 2007 report.<sup>54</sup> "Only Lithium from the Brine Lakes and Salt Pans will ever be usable to manufacture batteries: the Spodumene deposits can play no part in this". Following Evans, I seriously questioned this statement. Strangely, Tahil (MIR), in his second report<sup>33</sup>, mentions that it's easier to produce battery grade  $\text{Li}_2\text{CO}_3$  from hard rock concentrates (spodumene and other lithium minerals) than from the lithium brines. This strangeness is compounded, because he also states that it's cheaper to produce the carbonate from the brines. This lithium carbonate is of chemical grade and, of course, must be further processed to achieve the 99.95% purity of battery grade, but, still and all, the question remains, isn't what's easier also what's cheaper to produce? Howsoever it may be, I agree with Evans<sup>11</sup> that if Tahil's high demand scenario becomes reality, the more viable spodumene, petalite and lepidolite sources of lithium will be developed or in some cases reactivated, though higher prices probably would be needed to justify the higher required investment costs for open pit or underground mines. Evans also reminds us that a considerable portion of China's chemical grade carbonate is still produced from spodumene. Added to this are the other potential lithium sources analyzed by Evans – the hectorites, oil field brines, the Salton Sea geothermal brine, and the Serbian jaderite deposit, among others.

What does Evans and other sources have to say about the evolution of demand for lithium and LCE? In 2007, SQM (Sociedad Química y Minera de Chile, S.A.) estimated a total lithium market consumption of 17,500 tonnes (corresponding to about 93,000 tonnes of LCE), with an average compounded annual growth rate of 7.5% over the preceding 10 years.<sup>23</sup> Eric Norris, Global Commercial Director for FMC's lithium division, also put the 2007 market demand for LCE at 93,000t.<sup>43,75</sup> This coincidence of lithium carbonate demand contrasts with the amount reported by Evans in his March 29<sup>th</sup>, 2008 report of 84,000 tonnes of LCE (about 16,000t Li).<sup>10</sup> However, it's interesting to note that Evans' estimate is close to Tahil's non-automotive  $\text{Li}_2\text{CO}_3$  demand (85,000t) for 2007. Since none was used in the automotive sector according to Tahil, this tonnage is total demand.<sup>33</sup> Evans stated that total LCE demand for 2008 ascended to 91,500 tonnes (95,000t in his August, 2009 report<sup>13</sup>), dropping to 70,000t in 2009 because of the economic downturn.<sup>14</sup> He also adds that an important producer estimated global demand for 2010 at about 94,000 tonnes of LCE. In the January, 2009 conference "Lithium Supply and Markets", organized by Industrial Minerals magazine, SQM's Patricio de Solminihac, Executive VP & COO,

presented a much higher range of estimates of  $\text{Li}_2\text{CO}_3$  demand for 2008 – 115,000 to 118,000 tonnes-- corresponding to an average yearly growth of 5 to 7% over the preceding 5 years. These high demand values, however, do not jive well with the 85,000 tonnes that SQM, in a former presentation to European investors, apparently estimated for 2007, having forecasted that by 2015 LCE demand would rise to about 160,000t, mainly as a result of some 10% of new cars (5 million/year) being powered by Li-ion batteries.\* In the Santiago conference de Solminihac added that SQM expected lithium chemical demand, excluding automotive batteries, to grow at an annual rate between 3 and 5% till about 2020.<sup>11,75</sup> It seems that generally the consensus at the conference was that 2008 was a year in which supply and demand were relatively in balance, but TRU Group's president thought that a lithium undersupply was possible by 2020. This opinion has since been contested by Evans as we shall see. The summary presented by Gerry Clark, the chairman of the conference, spoke of "lithium resources large enough to cover any rationally conceivable demand". Naturally, resources are one thing, but production (supply) sufficient to satisfy demand is another, which thus makes supply analysis a must. But, first, let's take a peek at some of the major producers' estimates of LCE demand for 2020 and one estimate even for 2030.<sup>12</sup> As was mentioned before, the three major brine producers (SQM, Chemetall, FMC) used 0.6kg  $\text{Li}_2\text{CO}_3/\text{kWh}$ . Together with the vehicle type and battery capacity, the LCE demand is tabulated, as noted by Evans:<sup>12</sup>

Vehicle Type	Battery Capacity (kWh)	LCE Demand (Kilos)
Mild HEV	2	1.2 (2 X 0.6 = 1.2)
PHEV	12	7.2
Pure BEV	25	15.0

This data apparently was used to project different demand scenarios.

SQM's forecast is for 2 scenarios, one considered conservative and the other deemed optimistic.

SQM's LCE Demand Estimate (2020 and 2030)<sup>12</sup>

2020			
CASE	EVs % of Fleet	% EVs with Li-ion Batteries	Tonnes LCE Demand
Conservative	9%	60%	20,000 to 30,000
Optimistic	20%	80%	55,000 to 65,000
2030			
Conservative	15%	75%	65,000 to 75,000
Optimistic	25%	90%	135,000 to 145,000

FMC estimated the penetration of the three types of electric vehicles:<sup>12</sup>

HEVs: 20-30%, PHEVs: 2-5%, Pure BEVs: 1-3%

Using this market penetration, besides other necessary data (total number of new vehicles, kgs  $\text{Li}_2\text{CO}_3/\text{kWh}$ , kWh/type EV), FMC projected the 2020 lithium carbonate equivalent demand for autos to be 70,000 tonnes. This added to FMC's estimate of 223,000 tonnes to

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\* This implies an estimated 50 million new cars per year. Tahil's estimate is 60 million for as far back as 2007.

satisfy conventional demand results in a total 2020 demand of 293,000 tonnes.<sup>13</sup> I already mentioned that the TRU Group inferred the global production of 50 million new cars per annum by 2020.

According to James O'Rourke's June, 2009 Madison Avenue Research Group report, the president of Chemetall, Steffen Haber, divulged the new LCE demand estimates for 2020, ranging from 90,000 to 145,000 tonnes,<sup>43</sup> a decade before SQM's optimistic 2030 forecast. O'Rourke also broached the idea of a "cultural push" related to increasing demand for lithium carbonate, which in essence takes into account political pressures to reduce dependence on fossil fuels both for environmental reasons and for international geopolitical considerations. Both aspects would supposedly lead to greater efforts to convert the vehicle fleet to different types of electric power, as exemplified by the \$2.4 billion set aside for grants by the U.S. government stimulus plan and administered by the DOE that I already commented upon. This "cultural" or, better yet, political push could upend all of the predictions of future lithium demand, which, as seen above, are notoriously varied. Evans emphasized this variability of LCE demand, due to differing assumptions. Just to get an idea of some of the 2009 investment projects in energy storage, among others in the U.S., O'Rourke listed the following in the automotive sector:<sup>43</sup> At least four battery companies, including LG Chem, Dow Chemical and A123, had plans for constructing a \$600 million R&D center in the state of Kentucky, pending the granting of DOE funds. Another project in Kentucky envisions not only R&D in Li-ion batteries, but eventually also in lithium-air batteries and Zn-air batteries. On the international scene, Toshiba in 2009 was set to massively produce its quick charging Li-ion batteries for HEVs. Nissan, Toyota, Mitsubishi Motors, Hyundai and Honda were all preparing to introduce battery-powered cars, as were the Chrysler-Fiat partnership, GM and Ford, not to mention the various European EV producers. Toyota, for example, stated in 2010 that it plans to introduce 8 new HEVs in the next few years, with the use of Li-ion powered batteries.\* Its plans also include the production of an all electric vehicle (BEV) and a PHEV. General Motors has already launched its PHEV Volt, Toyota its hybrid Prius and Nissan its BEV, the Leaf. Furthermore, GM even in 2009 was completing a large, in-house battery lab in the U.S. so as to assure a smooth interaction between the battery and the power management system.<sup>8</sup> These myriad developments, in words of O'Rourke, are what could lead to a "viral" increase of LCE demand, expressed in revamped annual growth. An Australian miner, Orocobre, which entered a joint venture with Toyota Tsusho to develop the Salar de Olaroz in Argentina, noted that the demand for lithium for use in Li-ion batteries is increasing at an annual rate of 35%, largely driven by automakers to comply with increasingly stringent emissions standards, while overall the demand for lithium is much lower, at about 7% per year.<sup>7</sup> A Canacord analyst placed a "speculative buy" on three small Canadian lithium miners (Lithium One, Western Lithium and Canada Lithium), apparently based on its

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\* Would this be a turnaround of Toyota's opinion regarding the use of Li-ion powered batteries? In 2008, the environmental strategy manager of Toyota's advanced technology group stated that "the future supply of lithium will not be able to sustain both the exponential growth in batteries for consumer electronics and a large automotive battery demand", thus, apparently accepting Tahil's version of an undersupply of lithium. This led to Toyota's decision to stick with NiMH batteries for its 2009 Prius. In the same year, another high executive of the advanced technology group predicted that "Li-ion batteries would be in vogue for only about a decade" and that "if people want an electric vehicle that goes 200 miles but doesn't cost \$100,000, that's not lithium, that's something else". Honda company in the same year, for much the same reasons, also declared that its 2010 Honda Insight would be powered by a nickel metal hydride battery.<sup>24</sup>

upbeat acceptance of SQM's 10 to 20% EV penetration forecast for 2020 and Canacord's own LCE demand expectancy of 286,000 tonnes for the same year.<sup>7</sup> According to the Canacord analyst, this demand will significantly outstrip current supply.

Evans, in his November 11, 2010 blog, presents the results of what may be one of the latest attempts at forecasting future Li<sub>2</sub>CO<sub>3</sub> demand.<sup>14</sup> A Dr. Duesterhoeft of the General Motors Strategic Planning Group, in a conference hosted in Seoul, after forecasting two scenarios of electric car sales for 2020, 2050 and 2070, arrived at the following LCE auto sector requirements for the same years.

Auto Sector LCE Requirement Estimates

<u>Electric Car Sales</u>	<u>Battery Skeptical</u>	<u>Uber (Ultra) Green</u>
2020	7.5 million	20.0 million
2050	?	?
2070	15.0 million	170.0 million
<u>Resulting LCE Requirements</u>	<u>Battery Skeptical</u>	<u>Uber (Ultra) Green</u>
2020	15,000 tonnes	35,000 tonnes
2050	150,000 tonnes	400,000 tonnes
2070	250,000 tonnes	750,000 tonnes

As is clearly seen in the table, the range of estimates is wide for each year. The uber green estimate of LCE for 2020 is more than twice the Battery Skeptical tonnage for the same year. The other far off years' estimates have such wide ranges that one shouldn't be overly optimistic regarding their validity. Structural changes in the world economy and possibly completely different battery chemistries other than Li-ion or vastly different green technologies could render these forecasts obsolete. Nevertheless, they do serve to heighten supply preparedness for at least the medium term. In addition to the above forecasted LCE demand in the medium and long terms, Evans posted a 7 to 10% estimated compound rate of growth of conventional uses, plus what may be demanded for large grid storage batteries, for example, for green technologies such as wind and solar electricity generating systems.<sup>14</sup> If Evans and de Solminihac of SQM are talking about the same conventional demand, excluding that corresponding to the auto sector, there is a considerable difference in their estimates (7 to 10% versus de Solminihac's 3 to 5%), though this may be due to the fact that de Solminihac's low range estimate was done more than a year before Evans' higher estimate towards the end of 2010 with updated information, or simply because demand estimates are notoriously difficult to statistically perform. Interestingly, in his December 10<sup>th</sup>, 2010 blog, Evans noted a 5% annual growth rate for "conventional" lithium chemical demand.<sup>15</sup>

Before embarking on the supply response estimates of different organizations and persons, contrasting their forecasts with those already summarized from Tahil's papers, I shall present some of Evans' estimates (and one corresponding to Cyril R.'s blog of April 4, 2009) of electric vehicle production taking into consideration his LCE demand data.

In his January, 2009 paper, Evans asserts that for each million tonnes of the lithium element recovered, 532 million vehicles (assuming a 10kWh battery) could be produced.<sup>\*,12</sup> Evans adds that the majority of electric vehicles will require less battery power, which would translate into more electric vehicle capacity. Why Evans now assumes 1 kg LCE/kWh instead of the 0.6kg/kWh that he often quotes, I don't know. If he had used the latter figure, 880 million vehicles potentially could be produced per million tonnes of lithium. In his November, 2010 paper<sup>14</sup>, Evans states that a million tonnes of lithium (5.32Mt of LCE) would be enough to produce 395M GM Volts or 250M Nissan Leafs. Unfortunately, he doesn't indicate how he calculated these numbers, that is, what values he used for kg Li<sub>2</sub>CO<sub>3</sub>/kWh and the battery power, kWh/vehicle. However, with his results, it's evident that the battery size would have to be larger than 10kWh/vehicle, which contradicts what he mentioned in his January, 2009 paper. Tahil's parameter values would have resulted in 237.5 million Volt class PHEVs.<sup>\*\*</sup> Cyril R., replying to Ecoworld's March 27<sup>th</sup>, 2009 blog and using Tahil's 2008 recoverable brine reserve estimate of an extremely conservative 4 million tonnes of lithium, has emphasized the fact that even with this minimum amount there would be no problem for the production of a billion EVs. He assumed the use of 4 kg of lithium per battery per vehicle.<sup>\*\*\*,8</sup> In his April 7<sup>th</sup> blog, he assumes lithium per vehicle between 1 to 2 kg, powered by LiFePO<sub>4</sub> batteries of 25 to 50 kWh. Taking Evans' 30Mt of available lithium resource (actually Evans' latest estimate –December, 2010-- is 34.5Mt of Li resources), Cyril R. calculates a potential production of 30 billion electric vehicles, meaning he used 1 kg of Li per vehicle and then, in allusion to Tahil's statement that there isn't enough lithium, he ends in a chipper note, "What are we worried about?" The trouble with his calculation is, first of all, that the 30Mt are the total resource. Evans prudently states that recoverable reserves would be between 50 to 60% of total resources,<sup>13</sup> let's say 18Mt of Li. But, these 18Mt are for all uses. In 2009, some 22% of end uses was for batteries, but that includes chargeable and non-rechargeable batteries, which would mean that some 4Mt were available for batteries, of which let's suppose half of that was available for car batteries. At 1 kg of Li per vehicle, instead of a whopping 30 billion EVs, the auto industry could have produced 2 billion, which is still an optimistic figure. Why Cyril R. presumes a battery capacity of only 1kg of Li per vehicle he doesn't say. In conclusion, and again with Evans, estimates vary considerably, which complicates lithium producers' supply decisions.

## V. SUPPLY ANALYSIS

I mentioned before that the lithium consulting company TRU Group's president, Edward Anderson, during the January, 2009 Santiago conference, forecasted an undersupply of lithium *vis-à-vis* demand by 2020 and that, therefore, another large chemical grade lithium supplier was needed to avoid the looming supply deficit,<sup>75,11</sup> since there had only been one new entrant, Rincón Lithium Ltd., at the Salar del Rincón in Argentina. Joseph Williams and James O'Rourke, of the Madison Avenue Research Group, seemed optimistic in their 2009 statements that new suppliers will enter the market as demand increases and that "strategic investors" had already begun positioning themselves

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\* 1 million tonnes Li is equivalent to 5.32 million tonnes LCE. Therefore,  
 $(5.32 \times 10^9 \text{ kg LCE}) / (1 \text{ kg LCE/kWh} \times 10 \text{ kWh/vehicle}) = 532 \text{ million vehicles}$

\*\*  $(5,320,000,000 \text{ kg LCE}) / (1.4 \text{ kg LCE/kWh} \times 16 \text{ kWh/Volt}) = 237.5 \text{ million Volts}$

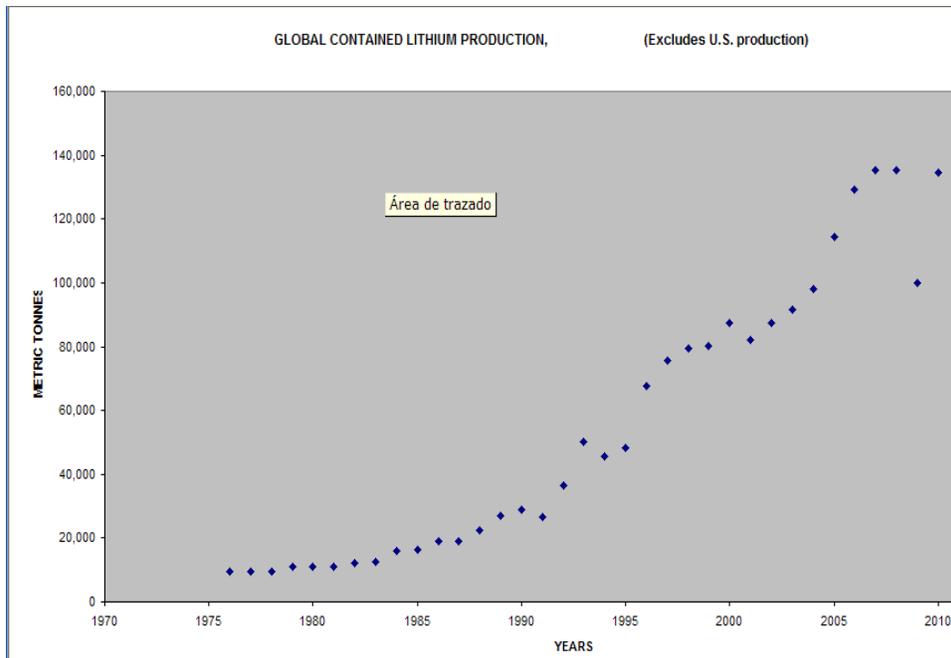
\*\*\*  $(4,000,000,000 \text{ kg Lithium}) / (4 \text{ kg Lithium/EV}) = 1 \text{ billion EVs}$

in the hectorite clays and oil field brines. They did seem pessimistic regarding the hard rock lithium pegmatites because of disadvantaged extraction costs compared to the brines. Evans, however, while recognizing that a rise in price will be needed to make investments worthwhile, is optimistic that spodumene pegmatites will be reactivated (including the shut down North Carolina spodumene mines) and developed if there is a sustained increase in the demand for lithium carbonate, such as Tahil anticipates. The pegmatite deposits of Canada are another example. Not taking into account Tanco's (Tantalum Mining Corporation of Canada Ltd.) spodumene mine, other Canadian sources may have a potential 20 years of production at the rate of 50,000 tonnes of LCE per year, i.e., a possible total of around 1Mt. As Evans states, the technology for obtaining lithium carbonate from spodumene and the other hard rock lithium pegmatite minerals is well understood, as is testified by the continuing important Chinese production of carbonate from national and imported Australian spodumene.<sup>11</sup> Regarding the lithium undersupply forecast for 2020 at the Santiago conference, let's start with the situation at the beginning of 2009. In terms of LCE, global production capacity was estimated to have been 115,000 tonnes per annum (tpa), while total demand was approximately 95,000, indicating more than enough production potential to meet demand.<sup>12</sup> Evans indicates in his November 11, 2010 blog that the capacity of production had increased to about 130,000 tonnes of LCE and that 2010 demand according to a major producer was estimated at about 94,000 tonnes, which again points to a continuing excess 2010 capacity of 36,000 tonnes (prudently rounded down by Evans to 35,000 tonnes).<sup>14</sup> After summing target production plans of numerous lithium producing companies plus new projects but excluding SQM and major Chinese brine producers, Evans compares the 264,000 tonnes of phased-in lithium carbonate production expansion with the estimated 2010 demand of 94,000 tonnes, indicating an excess of 170,000 tonnes, thus inducing him to state that "there well could be a major over-supply problem in the short term". The comparison implicitly assumes that production increases but demand is static, whereas demand most probably will increase in the future, excepting cyclical economic downturns. Would this possible short run oversupply dissipate eventually to the 2020 undersupply predicted at the Santiago conference should there be no new important producers? From what I glean from Evans' different papers is that production will be forthcoming to meet even substantial increases in demand, due to rising prices, so that it appears Evans eschews an undersupply problem on the horizon. Another observation of interest: As mentioned, the 264,000 future estimated LCE production does not include the major producer, SQM, since it did not announce expansion plans except to say it intended to maintain its market share. If the company's current lithium carbonate production capacity of 40,000 tonnes is added to the 264,000 expected world capacity, the result (304,000t) is close to Tahil's high  $\text{Li}_2\text{CO}_3$  production scenario for 2020 of 308,000 tonnes, though it's important to add that Tahil's estimate is only for the brine sources of lithium while Evans' includes brines and other sources. Abell and Openheimer used MIR's LCE yearly production supply estimates as a basis for allocating this LCE supply to three end use categories: batteries for HEVs and PHEVs, non-automotive battery uses, and other uses. Without going into the details of their assumptions, the conclusion is that "there is not a supply shortage until close to 2020" and that "contrary to MIR's conclusions, there is actually a supply surplus until then".<sup>1</sup> This would seem to corroborate Evans' predictions regarding a short term oversupply, but leaves the question regarding an undersupply by 2020 open to discussion. The USGS estimates of global LCE production unsurprisingly differ from other estimates.

For example, Evans' January, 2009 estimate of 115,000 tonnes capacity (corresponding to 2008) is much lower than the USGS production of 135,000 tonnes, although, due to the economic downturn in 2009, production according to the USGS dropped sharply to 100,000 tonnes.

WORLD PRODUCTION, METRIC TONNES OF CONTAINED LITHIUM (Excluding U.S. production to avoid disclosing proprietary data) Source of Data: Various USGS Mineral Surveys			
YEAR	METRIC TONNES* Li	SOURCE USGS	TONNES LCE***
1976	1,814		9,650
1977	1,814		9,650
1978	1,814		9,650
1979	2,041		10,858
1980	2,041		10,858
1981	2,041		10,858
1982	2,268		12,066
1983	2,359		12,550
1984	2,994		15,928
1985	3,084		16,407
1986	3,600		19,152
1987	3,600		19,152
1988	4,200		22,344
1989	5,100		27,132
1990	5,400	450494.pdf (from 1994)	28,728
1991	5,000	450495.pdf (from 1995)	26,600
1992	6,860	450496.pdf (from 1996)	36,495
1993	9,430	450497.pdf (from 1997)	50,168
1994	8,540	450498.pdf (from 1998)	45,433
1995	9,070	450499.pdf (from 1999)	48,252
1996	12,700	450400.pdf (from 2000)	67,564
1997	14,200	450401.pdf (from 2001)**	75,544
1998	14,900	lithimy02.pdf (from 2002)	79,268
1999	15,100	lithimy03.pdf (from 2003)	80,332
2000	16,400	lithimy04.pdf (from 2004)	87,248
2001	15,400	lithimy05.pdf (from 2005)	81,928
2002	16,400	lithimy06.pdf (from 2006)	87,248
2003	17,200	myb1-2007-lithi.pdf (from 2007)	91,504
2004	18,400	myb1-2008-lithi.pdf (from 2008)	97,888
2005	21,500	myb1-2009-lithi.pdf (from 2009)	114,380
2006	24,300	myb1-2009-lithi.pdf (from 2009)	129,276
2007	25,400	myb1-2009-lithi.pdf (from 2009)	135,128
2008	25,400	mcs-2010-lithi.pdf (from 2010)	135,128
2009	18,800	mcs-2011-lithi.pdf (from 2011)	100,016
2010	25,300	mcs-2011-lithi.pdf (from 2011)	134,596

\* 1976-1985 data converted from short tons to metric tonnes  
\*\* 1997: does not include 1200 tonnes of lithium equivalent corresponding to 6400 tonnes lithium carbonate, from Silver Peak, Nevada, U.S. Cyprus Foote; information from Joyce Ober, USGS 450497.pdf, p.1  
\*\*\* 5.32 tonnes of LCE correspond to 1 tonne of Li.



As indicated by the USGS 1994 lithium summary publication (Ober, 450494.pdf), in this year Chile and the United States were the leading producers of lithium carbonate, while Australia, Canada, China, Portugal, Russia and Zimbabwe produced significant quantities of either lithium compounds or ore concentrates. Argentina, Brazil and Namibia produced smaller quantities of concentrates at this time. Rwanda, South Africa and Zaire (now the Democratic Republic of Congo) were former producers of mineral concentrates. Additionally, lithium pegmatites had been detected in Austria, France, India, Ireland, Mozambique, Spain, and Sweden, but without the geologic and cost characteristics conducive to economic exploitation. Subsurface brines had already been identified in Argentina, Bolivia, China and Israel. By the time of the USGS 2011 lithium summary report (Jaskula, mcs-2011-lithi.pdf), Chile is the leading lithium carbonate producer, while Argentina, China and the United States are also major producers. A large percentage of lithium carbonate produced in South America is exported to the U.S.<sup>23</sup> The importance of U.S. lithium compound imports from South America is seen in the following table:<sup>41</sup>

U.S. Lithium Imports, Percentage by Country

Year	Chile %	Argentina %	Others %
2005	75	24	1
2006	60	37	3
2007	59	38	3

Besides the U.S., the other producers of downstream lithium compounds from imported lithium carbonate are France, Germany, Japan, South Korea, Russia, Taiwan and the UK. Nevertheless, the U.S., as of 2010, remained the leading producer of downstream, value-added lithium materials, which company-wise was from the output of two firms, Chemetall and FMC.<sup>65</sup> The major producers of lithium ore concentrates are, in order of importance, Australia and Zimbabwe. As is seen in the table below, Bolivia has yet to begin producing

from its huge Salar de Uyuni lithium brine. Rio Tinto Zinc is still in the development stage of its unique jadarite deposit in Serbia.

U.S. Geological Survey (USGS)* Mineral Commodity Summaries									
World Mine Production									
Metric Tonnes Contained Lithium									
Country	1994	1995	1996	1997	1998	1999	2000	2001	2002
United States	W	W	W	W	W	W	W	W	W
Argentina	8	8	8	8	1130	200	200	200	946
Australia	1700	1700	3700	2800	2100	2200	2400	2000	3140
Bolivia									
Brazil	32	32	32	32	32	32	30	220	224
Canada	630	660	690	1600	700	710	710	700	707
Chile	2000	2000	2700	4100	4700	5300	5300	6800	5920
China	320	320	2800	2900	3000	2300	2400	2400	2400
Congo									
Namibia	40	50	48	40	28				
Portugal	180	160	160	160	160	140	140	200	190
Russia	800	800	800	2000	2000	2000	2000	2000	
Serbia									
Zaire									
Zimbabwe	380	500	500	500	1000	700	700	700	640
Total**	6100	6300	11000	14000	15000	14000	14000	15100	14200
* Various USGS Reports Used									
**Rest of World Total (Rounded) (Excludes U.S. Proprietary Data Production)									
W: Proprietary Data Withheld									

U.S. Geological Survey (USGS)*								
World Mine Production								
Metric Tonnes Contained Lithium								
Country	2003	2004	2005	2006	2007	2008	2009	2010
United States	W	W	W	W	W	W	W	W
Argentina	960	1970	1980	2900	3000	3170	2200	2900
Australia	3450	3930	3770	5500	6910	6280	6280	8500
Bolivia								
Brazil	240	242	242	242	180	160	160	180
Canada	710	707	707	707	707	690	210	
Chile	6580	7990	8270	8200	11100	10600	5620	8800
China	2500	2630	2820	2820	3010	3290	3760	4500
Congo								
Namibia								
Portugal	190	320	320	320	570	700		
Russia		2200	2200	2200				
Serbia								
Zaire								
Zimbabwe	480	240	260	600	300	500	400	470
Total**	15100	20200	20600	23500	25800	25400	18800	25300
* Various USGS Reports Used								
**Rest of World Total (Rounded)								
W: Proprietary Data Withheld								

U.S. Geological Survey, Lithium Minerals & Brines									
Metric Tonnes, Various Mineral Surveys									
COUNTRY PRODUCTION	1981	1982	1983	1984	1985	1986	1987	1988	1989
Argentina:									
Spodumene and amblygonite	28	125	168	24	22	184	178	119	120
Lithium Carbonate									
Lithium Chloride									
Australia, spodumene		90	1100	7200	12300	12703	22279	30000	40000
Brazil, concentrate	2868	3060	2339	897	963	2059	2503	1471	1575
Canada, spodumene				96	330	3500	11500	14000	14000
Chile:									
Lithium carbonate, brine				2326	4959	4458	6139	7332	7508
Lithium Chloride									
Lithium hydroxide									
China, carbonate	15400	15400	18,500	16500	16500	15000	15000	15000	15000
Namibia, chiefly petalite	1392	1146	860	970	2160	835	1816	1642	1398
Portugal, lepidolite	990	998	601	1086	880	1800	9380	14109	18264
Russia, minerals not specified									
USSR	60600	60600	60600	60600	60600	55000	55000	55000	55000
United States, brine	W	W	W	W	W	W	W	W	W
Zimbabwe*	18126	10788	21657	25270	30165	32760	14959	15073	20647
*Zimbabwe: amblygonite, eucryptite, lepidolite, petalite, spodumene									

U.S. Geological Survey, Lithium Minerals & Brines									
Metric Tonnes, Various Mineral Surveys									
COUNTRY PRODUCTION	1990	1991	1992	1993	1994	1995	1996	1997	1998
Argentina:									
Spodumene and amblygonite	69	287	620	300	400	400	400	697	700
Lithium Carbonate									6000
Lithium Chloride									2500
Australia, spodumene	40000	40400	42516	52900	45987	81841	117094	88399	63190
Brazil, concentrate	475	1560	1600	1600	1600	1600	1600	6948	9485
Canada, spodumene	12000	12000	18500	18900	20000	21000	22000	22500	22500
Chile:									
Lithium carbonate, brine	9080	8580	10823	10369	10439	12943	14180	24246	28377
Lithium Chloride									
Lithium hydroxide									
China, carbonate	15000	15500	7220	8248	9050	12800	15000	15500	13000
Namibia, chiefly petalite	1264	1190	1162	742	1861	2611	1972	1019	500
Portugal, lepidolite	10600	10000	15904	13289	11352	8740	7626	6883	7000
Russia, minerals not specified									
USSR	55000	50000							
United States, brine	W	W	W	W	W	W	W	W	W
Zimbabwe*	19100	9190	12837	18064	25279	33498	30929	49833	28055
*Zimbabwe: amblygonite, eucryptite, lepidolite, petalite, spodumene									

U.S. Geological Survey, Lithium Minerals & Brines											
Metric Tonnes, Various Mineral Surveys											
COUNTRY PRODUCTION	1999	2000	2001	2002	2003	2004	2005	2006	2007	2008	2009
Argentina:											
Spodumene and amblygonite	700	700	700								
Lithium Carbonate	1592	2161		906	2850	4970	7288	8228	8863	9984	7000
Lithium Chloride	2794	5182	4512	4729	4700	6303	8416	8336	8828	7800	5500
Australia, spodumene	75824	65504	79859	79085	124410	118451	173365	222101	192277	239528	200000
Brazil, concentrate	11122	10875	9084	12046	9755	9084	8924	8585	7991	8000	8000
Canada, spodumene	22500	22500	22500	22500	22500	22500	22500	22500	22500	22000	10000
Chile:											
Lithium carbonate, brine	30231	35869	31320	35242	41667	43971	43091	46241	51292	48469	25154
Lithium Chloride						494	681	1166	4185	4362	2397
Lithium hydroxide							504	3794	4160	4050	2987
China, carbonate	12500	13000	13000	13000	13500	14000	15000	15000	16000	17500	20000
Namibia, chiefly petalite											
Portugal, lepidolite	14862	9352	11571	16325	24606	28696	26185	28497	34755		
Russia, minerals not specified	2000	2000	2000	2000							
USSR											
United States, brine	W	W	W	W	W	W	W	W	W	W	W
Zimbabwe*	36671	37914	36103	33172	12131	12131	37499	30000	30000	25000	20000
*Zimbabwe: amblygonite, eucryptite, lepidolite, petalite, spodumene											

In order to get a clearer idea of the ability of the lithium mining industry to expand and satisfy the varied end use demands for its products, it may be helpful to list individual companies' evolving production and capacity levels. In Argentina, as long ago as 1994, FMC was developing its lithium carbonate project in the Salar del Hombre Muerto in Catamarca Province and estimated that by 1996 or 1997 it would be producing about 4,500 tpa, with a future potential increase to 16,000t subject to prevailing demand conditions. This estimated potential for the future was apparently raised to 20,000 tpa of LCE according to the USGS 1997 report.<sup>40</sup> The same corporation still mined spodumene near Bessemer City, North Carolina in 1994, but had plans to phase out its production there upon completing the development project at the Salar del Hombre Muerto. In effect, the Argentine project was completed in 1997 with the resulting closure of the North Carolina mine and carbonate plant, but, as of July, 1999 FMC suspended production at its 12,000t capacity lithium carbonate plant at Hombre Muerto, having signed a long term agreement with SQM of Chile, by which this company would supply FMC with its carbonate requirements.<sup>40</sup> Nevertheless, FMC continued operating the 5,500t LiCl production line at the salar.<sup>39</sup> Apparently, at the Salar del Hombre Muerto FMC's "production of both compounds reached record levels in 2004", as reported in USGS's 2005 mineral year book,<sup>41</sup> and in 2006 the company satisfied its lithium carbonate needs with material produced at its own facilities as well as carbonate processed by SQM and shipped to FMC in Argentina under the long-term contract.<sup>39</sup> FMC's lithium carbonate production was estimated to have reached more than 8,500t in 2007, following continuous increases since 2002 when the carbonate production line was re-launched, though still remaining below its 12,000 tpa capacity.<sup>23</sup> Apparently by 2008 capacity was estimated at 17,000 tpa and production at close to 10,000t, but in the world economic downturn of 2009 it was

estimated to have dropped to 7,000t, a 30% reduction from 2008. As of 2011, FMC planned a large carbonate capacity of 23,000 tpa, an increase of more than 30%. LiCl production capacity at Hombre Muerto had been expanded to 8,500 tpa in 2007, while the estimate for production in 2008 was 7,800t, falling to 5,500t in 2009.<sup>23</sup>

A new player in Argentina's lithium brines scene in 2005 was Admiralty Resources of Melbourne, Australia, with rights to the development of the Salar del Rincón brine resources. In this year the company announced its expected initial capacity of LCE to be 12,000 tpa and the production of LiCl from the brine to begin in 2007. Admiralty (ADY) continued developing the Rincón resource in 2007 and announced a design capacity for 10,000 tpa of Li<sub>2</sub>CO<sub>3</sub> (which in 2008 was stated at 17,000t), 4,000 tpa of Li(OH), and 3,000 tpa of LiCl. January, 2008 marked the date of the first unrefined Li<sub>2</sub>CO<sub>3</sub> production and the first commercial production was expected to be on stream by mid 2009. ADY had announced that it planned to form a separate company, Rincón Lithium Ltd., by April, 2008 to exploit its concession.<sup>23</sup> However, towards the end of 2008 ADY's brine project was purchased by an equity company registered in Cayman Island, the Sentient Group. In 2009 Sentient's Rincón Lithium Ltd. (formerly ADY's) announced its 2010 target lithium carbonate production level to be 1,500t, still far below the capacity output of 10,000 tpa. Argentina was intensifying its presence in the international lithium scene. Another Australian company, Orocobre Ltd., began an exploration project at the Salar de Olaroz in 2008 and in the same year Canadian Latin American Minerals Inc. initiated the Salares Potash-Lithium project in northwest Argentina, besides agreeing to purchase another property at the Salar de Cauchari. In 2009 Orocobre declared an initial future lithium carbonate target production of 15,000 tpa.<sup>23</sup> Though without a specified date, it probably reflects the joint venture agreement between Orocobre, the producer, and Toyota Tsusho Corp. (a supplier of Toyota Motor Corp), Panasonic Corp. and Sanyo Electric Co. Ltd. Also in 2009, the Canadian company, Lithium Americas Corp., launched its Cauchari-Olaroz Salares project in northwest Argentina as part of a strategic investment agreement with Mitsubishi Corp. Lithium Americas likewise signed an agreement with the Canadian auto parts manufacturer, Magna International Inc.<sup>23</sup> These five companies represent the growing concern of the automotive and battery industries to firmly secure low-cost lithium sources for the production of their EV batteries. Rodinia Minerals Inc. in 2009 was prospecting the Salar de Salinas Grandes located in Jujuy Province, Argentina, where earlier exploration had indicated possible lithium concentrations of about 400 ppm and a fairly low Mg/Li ratio of 3.75/1.

In 1994 Gwalia Consolidated Ltd. (also known as Sons of Gwalia Ltd.), at its Greenbushes lithium pegmatite property, Western Australia, (the only lithium ore concentrate producer at that time in the country and, besides, the largest in the world) planned to complete construction of its Li<sub>2</sub>CO<sub>3</sub> plant by 1995 with a capacity of 5,000 tpa and a planned initial production of 1000t in 1996. After only a year in operation in 1996, however, technical issues and cost considerations led to suspension of production. In 2007 Sons of Gwalia's Advanced Mineral Division was sold to the mining specialist consortium, Resource Capital Fund, and a new company, Talison Minerals Pty Ltd., was formed to mine the Greenbushes spodumene deposit. During the mining products 2007 boom year and the following year, about 60% of the world's supply of lithium minerals was produced by Talison (rising to about 70% in 2009), its spodumene concentrates being sold worldwide to glass and ceramics industries and, in addition to these industries in China, also for the production of Li<sub>2</sub>CO<sub>3</sub> in this country, whose markets pulled Talison's production nearly to

full capacity. In 2008 the spodumene concentrate capacity at Greenbushes had reached about 250,000 tpa and by 2009 apparently to 260,000t, while in this year spodumene production dropped 18% to 197,000t from that of 2008.<sup>23</sup> Evans updates this ongoing expansion by Talison to 2011, saying that the company is in the process of expanding various grades of spodumene ore production capacity to 480,000 tpa and, furthermore, that “a high percentage of current and future production will be feedstock for chemical production”.<sup>12</sup>

At the developing Mt Cattlin lithium pegmatite, also in western Australia in the vicinity of Ravensthorpe, Galaxy Resources Ltd. expected mine and processing plant construction to have begun by 2009 and that by late 2010 spodumene concentrate production would be in the order of 150,000 tpa.<sup>23</sup> This production facility is related to the projected commencement in 2010 of a 17,000 tpa lithium carbonate plant in Jiangsu, China. A significant portion of the planned battery grade carbonate production will be sold to Mitsubishi as stipulated in a agreement between this company and Galaxy. According to the 2011 USGS mineral commodity summary, at Mt. Marion (Mt. Cattlin is not mentioned) Galaxy Resources “commenced lithium concentrate production”, which will be converted into battery grade  $\text{Li}_2\text{CO}_3$  in China to supply the Asian market.<sup>65</sup> In his August, 2009 blog, Evans states that Galaxy’s carbonate production level in China would be “20,000 tpa to take advantage of lower sulfuric acid and soda ash prices there”.<sup>13</sup>

In Canada, among other lithium producing companies, Lithos Corp. was in the process of evaluating a promising spodumene deposit in Quebec during 1994. An added fillip to make the project worthwhile rests upon the low cost electricity in this Canadian province. Jumping ahead to 2000, Tantalum Mining Corp. of Canada (Tanco), a subsidiary of Hudson Bay Mining Co., operated a spodumene mine and concentration plant at Bernic Lake, Manitoba. By 2008 the plant had a concentrate capacity of 24,000 tpa. Due to a reduction of demand for its spodumene concentrate by the ceramics and glass industries, Tanco suspended its operations in September, 2009. The pegmatite straddles the Manitoba-Ontario border, which, on the Ontario side near Separation Rapids, in 2000 was being developed by Avalon Minerals Ltd. The project had as its goal the production of a high grade petalite concentrate, mostly destined to be exported to the glass and ceramic industries in the Ohio River valley, with plans to increase concentration plant capacity. However, by 2003 the plans had changed from a petalite product to the extraction of a high grade lithium, low iron feldspar. Then, by 2007, presumably the company (now referred to as Avalon Ventures Ltd. in the USGS report<sup>23</sup>) was investigating the possibility of extracting a lithium product suitable for the blooming Li-ion battery market. Backtracking to the situation in 2003, at a site owned by Emerald Fields Resource Corp. on the pegmatite between the Tanco and Avalon claims, Amzin Minerals Ltd. (the holding company of Bikita Minerals Ltd., the Zimbabwe petalite miner) planned to mine and concentrate petalite. Other Canadian companies with lithium pegmatite prospects in the Separation Rapids region were Champion Resources Ltd. and Gossan Resources Ltd. Another company, Houston Lake Mining Inc. had claims on a lithium pegmatite at Pakegama Lake, Ontario and development in 2003 was advancing to the east at Raymor Industries’ La Motte, Quebec open pit spodumene mine, from which, after the construction of a concentration plant, the spodumene ore concentrate would hopefully be used in a innovative process directly producing lithium metal.<sup>39</sup> Another spodumene bearing permatite near Moblan, Quebec was being prospected in 2007 by Globe Star Mining Corp. for possible use in the ceramics and glass industries. An economic evaluation of the property was completed in 2008 and in

2009 the company announced a target spodumene concentrate production of 22,000 tpa. To top off the sprint towards lithium projects in 2008, Channel Resources Ltd. signed a letter of intent with Polaris Capital Ltd. to acquire the Fox Creek Lithium Brine project in Alberta, whose potential lithium concentration presumably is equivalent to the Clayton Valley (Silver Peak), Nevada brines. Then, there was Lithium One exploring a lithium prospect in the far north James Bay area in 2009.<sup>23</sup>

During 2008 Canada Lithium Corp was developing a lithium brine prospect in Esmeralda County, Nevada and, additionally, was also prospecting six different possible brine locations in the Great Basin area. The company also purchased a Quebec lithium property complete with an underground mine, concentration plant and chemical plant that previously produced (1955-1965)  $\text{Li}_2\text{CO}_3$ ,  $\text{LiCl}$ ,  $\text{Li}(\text{OH})$  and spodumene concentrate. In 2009, Canada Lithium and Mitsui Co. Ltd. of Japan signed an agreement, the terms of which gave the Japanese company the right to market Canada Lithium's potential battery grade lithium carbonate production of 22,000 tpa in Japan, China and South Korea.<sup>23</sup> Meanwhile, Western Lithium Canada Corp., out of Vancouver, British Columbia, was in the process of evaluating five lithium-rich hectorite projects in the Kings Valley, Nevada area in 2008 and by 2010 had completed a drilling program on two of the five projects.<sup>23</sup> In 2009, the company set its LCE target production rate at 25,000 tpa.<sup>13</sup> Rodinia Minerals Inc., also with its main office in Vancouver, purchased 250 mining claims adjacent to Chemetall Foote's lithium brine property in Clayton Valley, Esmeralda County, Nevada from GeoXplor Corp., as reported in the 2009 USGS mineral year book. Another firm, American Lithium Minerals Inc., acquired several lithium brine prospects in Esmeralda County from the same company in 2010.

Turning to the prodigious Salar de Atacama in northern Chile, SQM (Sociedad Química y Minera de Chile) in 1994 was developing a large project for the production of potash and  $\text{Li}_2\text{CO}_3$ , with a LCE target of 9,000 tpa by the end of the century. The company commenced continuous production of lithium carbonate in November, 1996 and shipped its first commercial product at the end of the year from its plant at the port of Antofagasta. The former 9,000 tpa target production of  $\text{Li}_2\text{CO}_3$  had by 1997 been doubled to 18,000 tpa,<sup>40</sup> subject to the successful full capacity completion of SQM's so-called Minsal S.A. operation, which in 1997 would catapult Chile to number one in the world ranking of lithium carbonate producers ahead of the U.S.<sup>40</sup> Together with Cyprus Foote (see below) and FMC's Salar del Hombre Muerto's operation in Argentina, this also meant that South America would become the world's leading lithium producer. Development of SQM's concession had advanced rapidly, its  $\text{Li}_2\text{CO}_3$  plant capacity at Antofagasta having jumped to 23,000 tpa by 2003, producing at 27,000t full capacity in 2005 and programming a target capacity of 40,000t by 2008. In late 2005, the company had finished construction of its 1,000 tpa capacity  $\text{Li}(\text{OH})$  plant, which had been expanded to 6000t by 2009.<sup>23</sup> Pointing to its international presence, SQM reported that its share of the world lithium carbonate market had grown to 40%,<sup>41</sup> which, in its 2007 report was reduced to 31% (30% in 2008).<sup>23</sup> This report also mentioned that the lithium carbonate capacity would reach, not the 40,000t formerly expected, but even more, 42,000 tpa by mid 2008, the estimated completion date. Evans reports that the 40,000 tpa capacity figure is maintained even in 2011 and that SQM is determined to preserve its world market share of lithium carbonate.<sup>14</sup> The company is currently pumping enough brine, with an average contained lithium grade of 2,700 ppm, to reach a potash production rate of about 1.5 million tpa (860,000t of potash production capacity in 2009<sup>13</sup>), though for 2011 Evans sets the expected capacity at 1.2M tpa.<sup>15</sup> This

translates into a volume of lithium in the extracted brine far in excess of the capacity 40,000 tpa of LCE. This huge excess, estimated at approximately 400,000 tpa of LCE in 2011 (200,000t in January, 2009 and 280,000t in August, 2009<sup>13</sup>) is reinjected into the aquifer. It's easy to understand that the LCE production expansion potential is enormous, as Evans says.<sup>14</sup> Sales in 2007 rose to 28,000t. Nevertheless the reported sales volume had dropped slightly to 27,900t in 2008 and to 21,300t in 2009, a 24% decrease from 2008, with an even greater drop in revenues (32%) due to the lower price driven by recession in consumer countries.<sup>23</sup>

The other company developing the lithium brines at the Salar de Atacama, Cyprus Foote, (during 1994 still a subsidiary of Cyprus Amax Minerals Co.) has produced at Atacama since 1984. In 1996 the company's reported production at its Antofagasta lithium carbonate plant was 14,000t. As well as FMC, Cyprus Foote mined spodumene from the 48 km long pegmatite belt in NC, but in 1991 its mine and  $\text{Li}_2\text{CO}_3$  plant at Kings Mountain were shut down, though the company's Silver Peak, Nevada brine operation had produced 6,400t of  $\text{Li}_2\text{CO}_3$  (equivalent to about 1,200t of Li) in 1997,<sup>40</sup> and the firm had completed a lithium hydroxide (LiOH) production facility in the same year. 1998 marked the year of Cyprus Foote's purchase from Cyprus Amax Minerals Co. by the German firm, Chemetall GmbH, the sale having included all of Cyprus Foote's assets in the U.S. and Chile. The producer, designated as Chemetall Foote, by 2003 had increased its Antofagasta  $\text{Li}_2\text{CO}_3$  plant capacity to 14,500 tpa, output from which it supplied feedstock for Chemetall's downstream production of lithium chemicals at its operations in the U.S., Germany and Taiwan. Chemetall Foote, through its Chilean subsidiary Sociedad Chilena de Litio (SCL), also responded to growing demand for lithium and its compounds by further increasing its carbonate capacity, which in 2007 was expected to rise to 23,000 tpa by some time in 2008 or 2009. The company's total carbonate capacity in Chile and the United States was estimated at 27,000 tpa in 2008, but, depending on market conditions, this capacity was projected to grow to 33,000t in 2010, 40,000t in 2015 and 50,000t by 2020 and even a further increase to 65,000 tpa (Evans says by 2020<sup>14</sup>) was envisioned by the company. In 2009, it stood at 31,000 tpa<sup>23</sup> and at 38,000t<sup>14</sup> in 2011, a significant increase from 2008. Chemetall also had short and longer term plans for the expansion of Li(OH) production capacity: 5,000 tpa for 2010, 10,000 for 2015 and 15,000 for 2020, again subject to prevailing market conditions. However, actual production of  $\text{Li}_2\text{CO}_3$  in 2008 was below capacity at 18,000t, although this tonnage was augmented with 4,000t of LiCl. Chemetall Foote placed its share of the global lithium products market at 50% in 2008 and 2009, with a 30% stated share of the specific  $\text{Li}_2\text{CO}_3$  market.<sup>23</sup> It's important to add that lithium compounds are only a part of Chemetall's economic output portfolio from the Atacama brine. The company also produces a large volume of potash (KCl and  $\text{K}_2\text{SO}_4$ ), which in 2008 was about 800,000t, besides a smallish amount of boric acid.

Undoubtedly in 2011, the two brine operators at the Salar de Atacama (SQM and Chemetall Foote, dominated the world lithium carbonate market. It is noteworthy that Evans considers the entire Salar de Atacama nucleus economically viable. Why? Because its lowest grades are higher than the highest grades in the brines of Argentina.<sup>15</sup> From this can be inferred SQM's and Chemetall's potential of capacity expansion.

In 1997 large scale  $\text{Li}_2\text{CO}_3$  production facilities were still absent in China. While this compound was produced at 13 small plants distributed in 6 different provinces, the largest plant only enjoyed a full capacity of about 8,000 tpa. Another 10 plants had capacities of less than 2000 tpa. Both local spodumene concentrates and some lepidolite plus important

imports of spodumene from Gualia's Greenbushes deposit in Australia were used as inputs for the production of Chinese carbonate, though these imports were also destined for China's glass and ceramic industries. Furthermore, the 2005 USGS mineral year book reported that China also imported processed  $\text{Li}_2\text{CO}_3$  from Chile and the U.S.<sup>41</sup> Interestingly, in 2003 China was the only country that continued producing lithium carbonate from hard rock ore concentrates, in part because China's lithium containing brines are located in very remote regions and in 2003 were still largely undeveloped, though production was for the first time reported. Additionally, at least two of the brine deposits have the disadvantage of high magnesium/lithium ratios. However, by 2005 operators at the Zabayu salt lake (MIR writes Zhabuye) in Tibet announced a  $\text{Li}_2\text{CO}_3$  capacity of 5000 tpa, which, in a 2007 announcement was expected to increase to an undated 20,000t. Nevertheless, in 2009 the capacity at Zabayu remained at 5,000 tpa. In 2005, the Canadian company, Sterling Group Ventures, in a joint venture agreement with Beijing Mianping Salt Lake Research Institute, had plans to develop another Tibetan brine deposit and projected expected future  $\text{Li}_2\text{CO}_3$  production to reach 5,000 tpa.<sup>41</sup> Evidently, brine operations in China were receiving priority attention. The Chinese firm, CITIC Guoan Lithium Science & Technology Co., came online with a 35,000 tpa capacity  $\text{Li}_2\text{CO}_3$  plant at the Taijinaier salt lake in the far northwestern Qinghai Province, the largest lithium plant capacity in China. The plant operated at a low 5,000 tpa in 2008. CITIC, in a joint venture with Chengdu Chemphys Chemical Industry of Sichuan, signed a letter of intent with Toyota Tsusho in 2009, the object being to supply the Japanese firm with battery-grade  $\text{Li}_2\text{CO}_3$ . Another lithium carbonate plant under construction in 2007 and scheduled for completion in 2008, with a planned capacity of 10,000 tpa, is also located in Qinghai Province but at the Chaerhan salt lake.<sup>23</sup> The plant was completed in 2009 and produced an initial 400t. In the same province at Dongtai salar a 3,000 tpa carbonate plant came on stream in 2008, with plans to increase capacity to 20,000t by an unspecified date. All of these lithium carbonate plants with input from brines were operating far below capacity in 2008 and 2009. Even so, the Chinese planned to increase their lithium carbonate brine capacity to 85,000 tpa by 2010.<sup>14</sup> The total capacity of  $\text{Li}_2\text{CO}_3$  production from minerals was estimated to be about 41,000 tpa in 2008, while the estimate of what was actually produced was vastly lower at 13,000t, though it increased to 15,500t in 2009. Furthermore, since the Chinese lithium mineral concentrates were thought to be of low grade, they were generally used as inputs for the glass and ceramics industries. On the other hand, the higher grade spodumene concentrates imported from Australia were mostly destined for production of battery grade lithium carbonate. This could be true when comparing some Chinese imports from Talison's Greenbushes deposit with China's own concentrates, but, according to the 2009 USGS report, in comparing Talison's own production, its lower grade spodumene was exported to China, while its higher grade was sent to other Asian countries, Europe and the United States, generally for use in the ceramics, glass, foundry and steel industries.<sup>23</sup> As mentioned in the paragraph devoted to Australia, in 2009 Galaxy Resources Ltd. announced its planned construction of a 17,000 tpa battery grade  $\text{Li}_2\text{CO}_3$  plant in China beginning in 2010.

As can be seen from the above placed tables, Brazil is a rather minor producer of spodumene ore concentrates, as exemplified by the output of concentrate at the site of the underground mine owned by Companhia Brasileira de Litio.

Another new but minor player in 2007 was Keliber Oy of Finland at its lithium pegmatite deposit. This company, controlled by the Norwegian Nordic Mining Co.,

received a permit to produce 6,000 tpa of  $\text{Li}_2\text{CO}_3$  from its spodumene concentrates. In 2007 production was projected to commence in 2010.<sup>23</sup> However, in 2008 the USGS reported that the carbonate plant to be constructed would have a capacity of only 4,000 tpa.

In 2008, Symbol Mining Corp. garnered venture capital to the tune of \$6.7 million for the development of a process to extract lithium from the Salton Sea Known Geothermal Resource Area (SSKGRA) in the Brawley Area of southern California.<sup>23</sup>

Although potential for important lithium production at the gigantic Salar de Uyuni in Bolivia had been known for many years, it was only in 2008, under the tutorship of Evo Morales' government, that the state owned company Comibol (Corporación Minera de Bolivia) announced its intention to build a pilot plant at the salar, which in the company's 2009 announcement consisted of an investment sufficient for the construction of a 30,000 tpa lithium carbonate plant. In September, 2008 New World Resource Corp. signed a letter of intent to acquire a 99% interest in the lithium-potash Pastos Grandes brine project located in southwest Bolivia.

An order of magnitude feasibility study at Río Tinto Zinc's Serbian jadarite deposit revealed a high percentage of  $\text{Li}_2\text{O}$  content.<sup>23</sup> In 2009, Río Tinto stated its intention to start  $\text{Li}_2\text{CO}_3$  production in about 2015. Evans reported that if the 2009 estimated ore reserves of 0.95Mt were mined continuously for 20 years, 60,000 tpa of LCE could be produced, plus a co-product of some 300,000 tpa of boric acid.<sup>12</sup>

Simply taking into consideration the above new project developers' target tonnages of LCE, Evans comes up with 228,000 tpa, which includes the following: Salares de Olaroz, Rincón, Cauchari in Argentina, Tibet, China, Salton Sea KGRA in California, 2 pegmatites in western Australia (Mt. Cattlin and Mt Marion), Western Lithium's pegmatite in Quebec, Western Lithium's hectorite deposit straddling the Nevada/Oregon border, and Río Tinto's jadarite deposit in Serbia.<sup>15</sup>

The above rather detailed description of expanding exploration and production activities of geologically diverse lithium containing deposits points to what Keith Evans has long emphasized, that rapidly increased demand, particularly for Li-ion batteries, will bring forth increased resources and reserves of lithium, not only from continental brine deposits but also from pegmatites and hectorites, as well as less conventional sources such as geothermal brines, the newly developing jadarite deposit and perhaps some oil field brines. Production no doubt will depend on higher prices to cover higher capital and extraction costs. It appears that the USGS nods affirmatively in the same direction as is stated in its 2008 mineral year book report on lithium. "The use of lithium-ion batteries in HEVs, PHEVs and EVs could greatly increase demand for lithium. As demand and prices rise, spodumene and other lithium resources that had been considered uneconomic might once again yield economically feasible raw materials for the production of lithium carbonate. New lithium mineral operations currently being developed throughout the world to produce battery-grade lithium carbonate demonstrate a changing climate conducive to increased sales of lithium."<sup>23</sup> All of this being true does not change the fact that the continental brines are the principal raw material for the worldwide production of  $\text{Li}_2\text{CO}_3$ , precisely because of their lower production costs in comparison to hard-rock ore mining and processing costs. Furthermore, most of the ore concentrates are still used directly in the ceramics and glass industries, not as feedstock for the production of lithium carbonate as well as other lithium compounds. More to the point, "lithium chemical production, except in China where spodumene dominates as feedstock and on a small scale in Brazil, is based exclusively on brines from Nevada, Chile and Argentina."<sup>14</sup> It's interesting to note that

throughout the world there was more than a doubling of lithium exploration in 2009 compared to 2008, mostly by Canadian and Australian companies, which is not surprising considering the long and fruitful mining experience of both countries. Within the U.S. the Nevadan continental brines and hectorites were a main focus of exploration companies in 2009, whereas in Canada there was emphasis on the Albertan oil brines and the pegmatites of the Canadian Shield. In Australia, development of pegmatites was a priority. Quite naturally, the continental lithium bearing brines of Chile, Argentina and Bolivia were the major focus of exploration and development in 2009 by both national and international mining firms.<sup>23</sup> As we've seen in some country analyses, demand for battery grade lithium carbonate has resulted in increased exploration and production operations worldwide, with augmented potential to increase supply. This has been seen also in a "tendency of Asian technology companies to invest in the development of lithium operations in other countries to ensure a stable lithium supply for their battery industries", not basically due to a cost difference or greater production efficiency, but to assure themselves of a diversified supply security.<sup>23</sup>

Evans also broached the important question of the production and supply response time.<sup>15</sup> The upgrading of the concentration plant and chemical plant would be the determining factor in the case of operating open pit or underground hard rock mines. In the case of "greenfield" brine operations, solar ponds must be built and a salt base laid down to support heavy harvesting equipment for the recovery of generally "non paying sodium chloride and mixed sodium/potassium chloride for potash production," before recovering the liquid LiCl. The case of expanding currently operating brine operations is, of course, simpler and less costly. For example, SQM and Chemetall can quite readily expand their capacity production, as Evans notes.

## VI. COSTS AND PRICES

First, as was mentioned before, it's important to consider that lithium and its compounds are not traded on commodity exchanges like copper, gold, zinc, oil and many other commodities, which results in face to face negotiations between the lithium producing companies and the consumer industry firms. Prices are frequently kept proprietary. For the same reason cost information is hard to come by. The upshot of the matter is that the data at one's disposal are dispersed, without continuous series and are meager. Nevertheless, it's important to analyze what is available.

Customs Unit Value, Lithium Carbonate, U.S. Imports, Dollars/Kg

Year	Chile	Argentina	Year	Chile
1996	\$2.70		2003	\$1.55
1997	1.96		2004	1.72
1998	1.67	\$1.98	2005	1.46
1999	1.46	1.88	2006	2.32
2000	1.45		2007	3.45
2001	1.44	1.60	2008	4.44
2002	1.59		2009	4.53

Based on various USGS lithium summaries

Lithium Carbonate Prices, Dollars/Kg, Various Years

Year	Chile	Japan	Argentina	China	ADY	SQM	MARG <sup>iv</sup>
1996	2.00						
1999*	2.20						
2005					2.75		
2006					5.50		
2007**	4.48	7.00	3.82	6.70	6.00		
2008**	5.20		4.62	6.50			
2009						6.20-6.60	6.61
2010***						5.10-5.30	

Based on various USGS lithium commodity surveys

\*October, 1999; \*\*Roskill Information Services (2007-2008): Chile, Argentina, China

\*\*\*Based on expected 20% decrease from 2009; iv: Madison Avenue Research Group

Glass Grade Spodumene (Talisson Minerals Pty Ltd), 5% Li<sub>2</sub>O, Dollars/Metric Tonne

Year	Prices	MARG* Prices
2008	\$308 to \$354	
2009	\$363 to \$408	\$380 to \$436
2010**	\$380 to \$430	

\*Madison Avenue Research Group, 5% Li<sub>2</sub>O, West Virginia, price/short ton converted to price/metric tonne

\*\*Expected target prices; Based on 3 USGS lithium surveys

Regarding lithium metal prices (not lithium carbonate), the price tendency in nominal terms of the element from 1952 to 1974 was graphically flat. In constant dollar terms lithium prices tended downward. However, beginning in 1974, prices tended to rise in both nominal and constant dollar terms, reaching a year end average nominal price of about \$95/kg in 1998, largely due to increased demand for lithium batteries.<sup>36</sup> But following convention, most prices are expressed in terms of lithium carbonate or, regarding ore concentrates, in Li<sub>2</sub>O prices, as expressed in the above tables.

In 1996, SQM (Sociedad Química y Minera de Chile), based on its project known as Minsal S.A. at the Salar de Atacama and its seaport lithium carbonate processing plant in Antofagasta, wishing to break into the international lithium carbonate market, reduced its offer price for the compound to \$1.98 (U.S. dollars) per kilogram, less than half Cyprus Foote's and FMC's offer prices.<sup>40</sup> However, when the company effectively marketed its product, the price had been raised slightly to about \$2/kg, and by October, 1999 the firm again raised its price by 10% to \$2.20. Once more, it must be remembered that SQM's price is company specific and is not an industry wide price, which doesn't exist. There were no specific price announcements by Chemetall and FMC towards the end of 2000, but these two companies did raise their lithium carbonate prices by 8% and \$0.22/kg respectively. Because of the difficulty to obtain average price quotes across the spectrum of producers, the U.S. import customs value and quantity imported may offer a plausible surrogate of per kilogram lithium carbonate prices and particularly their tendency in time. For the period comprehending 1996 to 2001, carbonate customs unit value from Chile decreased from \$2.70 to \$1.44/kg, rising about 7% to \$1.59 in 2002 and falling to the

slightly lower level of \$1.55 in 2003<sup>40</sup>, values much below the 1997 to 2001 published producer price of \$4.47/kg. Thus it is seen that published prices are not reliable as indicators of effective market price. But, lithium carbonate exported from Argentina to the U.S. in 2001 indicated a unit value of imports of \$1.60/kg, revealing a difference across countries. Year 2004 saw a rise of 11% to \$1.72 for the average customs unit value of  $\text{Li}_2\text{CO}_3$ , only to drop about 15% to \$1.46 in 2005, followed by a great increase of about 59% to \$2.32 in 2006, a 49% rise in 2007 to \$3.45, an added 26% increase to \$4.44 in 2008 and \$4.53/kg in 2009, principally due to soaring demand from lithium battery producers.<sup>23,41</sup> Again, these are customs unit values for U.S. imports. Lithium producers reported significantly higher effective prices for most lithium compounds than the customs unit import values, which for lithium carbonate is exemplified by Admiralty Resources' report that the price of lithium carbonate in 2006 had risen to about an equivalent of \$5.50/kg from \$2.75/kg the year before.<sup>41</sup> In 2007 ADY reported a further increase to \$6.00/kg, whereas Roskill's Letters quoted an equivalent of \$7.00/kg for the 1<sup>st</sup> quarter of 2007 in the Japanese market.<sup>23</sup> However, because of the economic slowdown, supplies of lithium and its compounds became plentiful and prices declined at the end of 2009, according to Clifford Krauss of the NY Times, the price of lithium carbonate dropping from about \$5/kg to somewhere near \$4/kg in the first quarter of 2010.<sup>25</sup> SQM of Chile foresaw the need to reduce its price of lithium carbonate, thus setting a target in 2010 between \$5.10 and \$5.30/kg, whereas in 2009 the range had been between \$6.25 and \$6.60/kg. In his December 10, 2010 blog, Evans quotes Western Lithium company's estimated selling price of \$6,600/tonne (\$6.60/kg) for battery grade lithium carbonate.<sup>15</sup> In spite of present world economic uncertainty, the major auto companies appear committed to ramping up production of HEVs, PHEVs and also pure EVs, so that demand of lithium compounds should increase in the future, impinging on future price heights. Nevertheless, even a large multiple of current prices would not have a significant impact on the cost of batteries since it has been estimated that the cost of the lithium contained in batteries represents only between 1% and 3% of the total cost of the battery.<sup>14</sup> Evans speaks of a Chemetall estimated lithium cost of less than 1% in Li-ion batteries,<sup>15</sup> while other analysts speak of less than 3% and that a ten-fold increase in the lithium price would have a minimal repercussion on the battery price.<sup>43</sup> FMC also estimated that the lithium cost is less than 1% of the final Li-ion battery cost, where the lithium in the cell comes to about 1.5% of the cell cost and the cell cost is about 50% of the total battery cost ( $0.015 \times 0.5 = 0.0075$  or .75%). This estimated cost structure was for a 25 kWh auto battery containing a 7% Li, 6% Ni, 25% Co, 2% Mn cathode.<sup>15</sup> Incidentally, cobalt per kilo is much more costly than lithium carbonate. As one blogger said, "We all know that lithium is neither an exotic nor expensive element. What makes commonly used lithium batteries expensive is cobalt in the cathode, and with that now being replaced with other alternatives (Lithium hexafluorite phosphate and manganese) this problem is going away"<sup>2</sup>. Another blogger, George Hawley, pointed out an added potential problem, that "there is another essential mineral requirement. This is natural graphite, the preferred material that forms the anode into which the lithium ion intercalates. The theoretical amount of graphite needed is 10.37 times that of lithium. In actuality, due to inefficiencies, the amount is 20-24 times. The main producer of natural graphite is China. There is only one producer in North America (Mexico) and it is near the end of its reserves." Hawley adds from his viewpoint of the Western industrial economies that "unless natural graphite sources are developed in North America and Europe, when we switch to EVs, we will switch from dependence on Saudi Arabia to

dependence on China.”<sup>20</sup> Abell and Oppenheimer (A&O), as of December, 2008, estimated that a typical EV car battery would cost a consumer between \$3,000 and \$10,000. At a price of \$7/kg, the required lithium material for a large BEV (35kWh) would be less than \$80 (10.5kg Li x \$7/kg), which for a \$3000 battery is less than 3% of the total battery cost, and for a \$10,000 battery is less than 1% of the battery cost. Therefore, as A&O proclaim, “The cost of lithium is not the major driver in the manufacturing process and there is no reason the market should not tolerate an increase in the cost of lithium. Although the overall price of the batteries needs to come down to increase widespread usage, this is heavily dependent on manufacturing processes and reductions achieved from economies of scale”.<sup>1</sup> What is the impact on producers of lithium carbonate of a large rise or fall in the compound’s price? In the case of FMC, the sale of lithium compounds is actually a modest proportion of its income so that a fluctuation of price has a rather minor impact on earnings. The same is true for SQM, the largest lithium producer in the world. In fiscal year 2008, “their lithium business represented approximately 11% of total revenues”<sup>43</sup>.

Concerning lithium production costs, they are considered to be lowest at the Salar de Atacama, due to its “high lithium concentrations, outstanding solar evaporation conditions and proximity to the coast”, in comparison to other less fortunate brines.<sup>13</sup> Besides the brine grade, the net evaporation rate is an important factor affecting capital costs since it determines the area of the evaporation ponds used to increase the grade of the processing plant feed.<sup>10</sup> Then too, grades will decline over time, which will require a continuing increase in the size of the ponds.<sup>11</sup> Remote salt pans, such as the Tibetan brines, necessitate huge investments in transportation infrastructure. Costs of lithium recovery from Rio’s jadarite deposit, the western United States’ hectorite deposits and the geothermal brines are still not estimated, nor are they known for the oilfield brines, though Evans tells us that studies were ongoing during 2009. Regarding the pegmatites, he informs us that costs vary depending upon the particular deposit, but that in a 2008 estimate by SQM, Chinese carbonate costs amounted to about an equivalent of \$4.40/kg and that the cost per kilo would be about \$5.50 to \$6.60 if the North Carolina deposits were reactivated.<sup>13</sup> The point to make is that with a very large possible demand for lithium particularly in the battery market, as Evans says, new sources will be discovered and existing sources will be augmented. Regarding the pegmatites and other higher cost sources than lithium brines, the impact on battery costs will be of minimal importance.<sup>8</sup>

I believe that A&O make a valuable and interesting observation: “The argument that there is not enough lithium is, in a way, not the point.”<sup>1</sup> They go on to say that changing from an oil dependency to a lithium dependency is absurd and untenable. Lithium does not have to power all of the more than one billion current vehicles. But, the one great advantage of lithium is that it is now available to get the EV market rolling. As A&O state, lithium batteries should not be abandoned for ‘lack of supply’, referring to what Tahil insists upon. However, the use of lithium in batteries to power electric vehicles is obviously not the only chemistry that should be soundly funded and intensely researched.

For example, MIR Group has done some digging into the ZnAir and Zebra (NaNiCl) battery technology, which it says is not resource constrained.<sup>32</sup> ZnAir technology has a very high specific energy (Wh/kg) and low cost, although presently its disadvantage is low specific power (W/kg), low cycle life and the battery must be equipped for CO<sub>2</sub> absorption from the entry air. The latter can be an advantage regarding the reduction of atmospheric CO<sub>2</sub> levels. Another advantage is the use of lightweight ZnAir batteries in large trucks. The Zebra (NaNiCl) battery has, according to MIR, a specific energy “superior to any

automotive Li-ion battery available or under development today” (as of July, 2010) and “is suitable for pure BEVs and could be used for PHEVs”, but “it is not suitable for power assist hybrids (HEVs)”. MIR goes on to state that if nickel should become scarce and therefore more costly, the Zebra technology can be adapted to use iron instead of nickel, therefore obtaining the Zebra (NaFeCl), Sodium Iron Chloride battery, with only a slight drop in the battery open circuit voltage and a fall in specific energy of only 9% in comparison to the NaNiCl version. The modified Zebra (NaFeCl), according to MIR, would be an “extremely inexpensive, rugged and high specific energy battery that could approach a cost of \$100/kWh and enable widespread adoption of BEVs and PHEVs”.<sup>32</sup> The point is that different battery technologies are being researched and should be researched more intensely with adequate funding. Besides, intense competition is the Mother of innovation.

## VII. STRUCTURE OF THE LITHIUM INDUSTRY

The following description of the evolving structure of the lithium producing industry is an attempt to agglutinate the dispersed company information of many previous pages. Some repetition will be discerned. Eschewing the production of lithium mineral concentrates of the inward oriented economy of the Soviet Union and the neighboring countries in its sphere of influence, during the 1970s the western world’s lithium chemical production was essentially dominated by a duopoly of Lithium Corporation of America (LCA) and Foote Mineral Company (FMC), both of which, as was mentioned before, processed spodumene concentrates from mines near Bessemer City and Kings Mountain, North Carolina. However, in 1975 FMC had already been purchased by Cyprus Minerals. Besides then becoming the owner of the Clayton Valley (also called Silver Peak), Nevada brine operation, Cyprus Foote in an agreement signed with the Chilean government agency, CORFO, owner of mineral claims covering the nucleus of the Salar de Atacama, formed SCL (Sociedad Chilena de Litio) to evaluate the salar in the mid 1970s\* and began production in a portion of the nucleus in 1984. Cyprus Foote in October, 1998 was absorbed by Chemetall GmbH (a subsidiary of Metallgesellschaft AG), which even later was purchased by Rockwood Holdings Inc., though production in Atacama is carried out by the subsidiary of Rockwood called Chemetall Foote (now also the producer at Clayton Valley, NV). In 1983 CORFO had invited bids with the object of developing much of the rest of the nucleus, with two companies, Amax Exploration and Molymet, submitting the winning bids against LCA (which had been purchased by FMC),. These two companies formed Minsal (Sociedad Minera Salar de Atacama), in which CORFO held a 25% equity share.<sup>11</sup> However, Amax sold its interest to SQM (Sociedad Química y Minera de Chile), a Chilean company and important producer of iodine and sodium nitrate used for fertilizer production, which meant that the duopoly was broken. Now there were two producers at the Salar de Atacama, Chemetall and SQM, in the latter of which Potash Corporation of Canada presently holds a major stake.<sup>25</sup> SQM began production of its main products, potassium chloride and potassium sulfate, and by-product lithium carbonate in 1996<sup>33</sup> and by 1997 had entered the international markets for these products.<sup>54</sup> FMC tried and failed to sign an agreement with the Bolivian government for the evaluation and eventual development of its pretended interest at the huge Salar de Uyuni, and then successfully negotiated with the Argentine government regarding the Salar del Hombre Muerto, a

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\*CORFO retained a 45% interest in SCL.

smaller brine, as Evans relates, but with a low Mg/Li ratio and which would produce a high grade LiCl not elsewhere available.<sup>11</sup> Because of the low cost reserves of Chile and Argentina, the last spodumene mine in North Carolina was closed in 1998, but as already mentioned by Evans, the mines could possibly resume production if prices should rise with sufficient demand for lithium compounds. Chile (SQM and Chemetall) and Argentina (FMC) became the dominant producers of lithium carbonate worldwide, with Chile being number one. However, recalling that SQM's agreement, valid in 1999, with FMC to supply the latter company's  $\text{Li}_2\text{CO}_3$  requirements, "the global market was divided evenly between Chemetall Foote and SQM except for smaller quantities from China and Russia"<sup>40</sup>. So it appears that the duopoly may have returned to the lithium carbonate market until FMC again began producing significant quantities of the compound at its Hombre operation in about 2004. Other important developers, but still not major producers of Argentine brines, are the two Australian companies Admiralty Resources (ADY) at the Salar del Rincón (now in the hands of the Sentient Group) and Orocobre in a joint venture with Toyota Tsusho at the Salar de Olaroz, still under development. Canadian companies, Latin America Minerals Inc. in 2008, Lithium Americas Corp. in 2009 and Lithium One initiated brine projects, and exploration company Rodinia Minerals Inc was at the Salar de Salinas Grande, all in northwest Argentina. In the early years of decade 2000, large lithium brine deposits were located in the Qaidam Basin in northwest China and, afterwards, major chemically complex brine discoveries were made in remote areas of the Tibetan plateau.<sup>10</sup> An example of an important Chinese brine development project in Tibet is that of Zabuye Salt Lake, in which Tibet Lithium New Technology Co. is the firm formed by a joint venture between China's Geologic Research Institute (20% equity), Tibet Mineral Development Co. (40%) and Yuxin Trading Co. (40%). The Canadian company Sterling Group Ventures also entered a joint venture with Beijing Mianping Salt Lake Research Institute at the Tibetan DXC salar.<sup>33,54</sup> A joint venture in western China involves Pacific Lithium Ltd. of New Zealand and the Qinghai Province government, which resulted in the creation of Qinghai Lithium Ltd.<sup>40</sup> Finally, also in Qinghai Province at the Taijinaier Salt Lake, CITIC Guoan Scientific and Technological Co. built a large lithium carbonate plant to exploit the lithium brine. Although China is ramping up production at the brine deposits, lithium carbonate output still lags far behind capacity and most of what is produced is channeled into the domestic market. Therefore, China cannot be considered a major player (i.e. exporter) in the international carbonate market. Bolivia's promising Salar de Uyuni is just that, still a promise. Although the state-run Comibol's target production is for 20,000 to 30,000 tpa of LCE and 400,000 tpa of potash, it seems that no specific target date has been set.<sup>13</sup> Lack of capital and know-how would point to the need for foreign capital and technology. The development of Uyuni could require some US\$500 million "for roads, water and energy infrastructure",<sup>50</sup> not to hazard an additional estimate for the deposit itself. As Clifford Krauss in his March, 2009 blog states, "that Bolivia is a remote, unstable country often hostile to foreign investment has helped spur interest in producing lithium in neighboring Argentina and Chile, in Australia and in the U.S."<sup>25</sup> Juan Carlos Zuleta, an economist in La Paz, Bolivia, emphasized in February, 2009 that "if we don't step into the race now we will lose the chance. The market will find other solutions for the world's battery needs."<sup>49</sup> Exploration in Canada as well as in a few more countries should be added. Several companies are active at brine deposits similar to those at Clayton Valley, among which is Western Lithium USA Corp. at the salt pan near Winnemucca, Nevada, which some analysts say might have the 5<sup>th</sup> largest potential in the world of lithium carbonate,

plus a large resource of potassium sulfate.\* Barring changes due to the economic crisis, Western Lithium hopes to open a major mine site by 2014. First Lithium Resources Inc., a Canadian junior mining company, is developing a project at the Leduc, Alberta lithium brine deposit,<sup>43</sup> and Channel Resources had an interest in Polaris Capital Ltd's Fox Creek brine prospect, also in Alberta. Other Chilean, Argentine and Bolivian brines that have been surveyed are: the Salar de Surrie, Chile; Salar de Lagunos; Salar de Copaisa, Bolivia. These salares, however, are not active producers.

Regarding the hard rock mineral deposits, one segment of the global lithium market besides the other segment corresponding to lithium chemicals and metals, Talison Minerals Pty Ltd., at the Greenbushes western Australia pegmatite, dominates the first mentioned segment with its low-iron spodumene production for direct usage in the glass and ceramics industries.<sup>14</sup> This company, now engaged in expanding its reserves, was formed after a consortium of investors purchased Sons of Gualia in late 2007.<sup>54</sup> Spodumene/tantalum prospects of recent development in western Australia are Galaxy Resources' Mt Cattlin and Mt Marion pegmatites. Much lesser low-iron petalite tonnages are extracted by Bikita Minerals in Zimbabwe and the same can be said concerning Portugal's lepidolite production. Another producer, Tantalum Mining Corp. of Canada (Tanco), formerly an important tantalum and by-product low-iron spodumene concentrate producer at its Bernic Lake property on the Manitoba/Ontario border, suspended its operation September, 2009 due to insufficient demand. Avalon Ventures, Emerald Fields Resource and Champion Minerals Ltd are all developing lithium prospects on the same pegmatite. First Lithium Resources Inc. has an option for purchasing 100% of Inco's Godslith spodumene-rich pegmatite dike southeast of Thomson, Manitoba. The dike possibly contains economic amounts of rare earth metals (Cs, Nb, Ga, Rb) as well as W, Li and Ba.<sup>43</sup> Other Canadian companies with lithium pegmatite prospects are: Lithos Corp., Raymor Industries, Lithium One, Canada Lithium Corp., and Globe Star Mining Corp., all located in Quebec, plus Houston Lake Mining Inc. in Ontario. Five other lithium pegmatites in different countries should be mentioned: Nordic's subsidiary Keliber Resources in Finland soon to enter spodumene concentrate production; Brazil's Companhia Brasileira de Lítio's minor production of concentrates; the Jiajika deposit in China; the Pervomaisky spodumene deposit in the Russian Federation which ceased production of lithium carbonate at Novosibirsk when SQM began flooding the market; and the huge Manolo and Kittolo pegmatites in the Democratic Republic of Congo, where never-ending violence and lack of transportation facilities are serious obstacles.<sup>33</sup>

To complete comprehension of the present and possible future structure of the lithium producing industry, the unconventional sources of lithium should be enumerated, for they may be important in the not far future. First of all the various hectorite deposits in the American west must be considered, especially the McDermitt Caldera hectorite on the Oregon/Nevada border being developed by Western Uranium Corporation's spinoff, Western Lithium. Simbol Mining's development of the geothermal brines known as the Salton Sea KGRA in southern California is a definite lithium possibility for the future, as are the Smackover oil brines of Arkansas, where Great Lakes Chemical Co. and Tetra Technologies have been exploiting the bromine content for many years.<sup>33</sup> The other new

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\* Phil Taylor in his June 17<sup>th</sup>, 2010 blog quotes a resource potential of 11Mt of Li<sub>2</sub>CO<sub>3</sub> with estimated potential production of 30,000t of LCE/year and 125,000t of K<sub>2</sub>SO<sub>4</sub>/year.<sup>55</sup>

unconventional deposit, as pointed out in various pages of this paper, is Río Tinto's jadarite deposit in Serbia.

K. Evans has emphasized that there are "at least 60 more projects worldwide in various stages of exploration" and at least a dozen in the U.S.<sup>55</sup> These projects are, as Evans states, evaluating lithium deposits. Most of the companies that I mentioned in the above paragraphs are doing just that: exploring and evaluating brines, pegmatites and the unconventional sources of lithium. There is, however, "one dominant lithium concentrate producer", Talison at Greenbushes in Australia and three dominant chemical producers: FMC, Chemetall (Rockwood Holdings), and the largest producer, SQM of Chile.<sup>15</sup> The structure of the producers' end of the lithium business is clearly a dominating oligopoly in the international market. China as mentioned is an importer and producer basically for its internal market. What Joseph Williams and James O'Rourke say may prove to be true: "...with a relatively small number of producers controlling a large percentage of global production, an effective oligopoly will make lithium a strategic commodity in decades to come ..."<sup>43</sup>

#### VIII. MEXICO'S LITHIUM/POTASSIUM SALAR

In 2009 the small mining exploration company, Piero Sutti S.A. de C.V., announced the discovery of a large lithium-potassium deposit sprawling along both sides of the border of Zacatecas and San Luis Potosi, and which includes the municipalities of Salinas de Hidalgo, Santo Domingo and Villa de Ramos in SLP as well as Pánfilo Natera, Villa González and Villa de Cos in Zacatecas.<sup>27</sup> In some accounts the mineral find covers an area of about 60,000 hectares<sup>27,45,50</sup>, while Martin Sutti Courtade, the director of the company, stated that the deposit has an area of some 40,000 hectares, according to the Latin American Herald Tribune.<sup>28</sup> On the other hand, the Secretaría de Economía through its Dirección General de Minas extended mining rights to the claims of Piero Sutti covering a little more than 47,000 hectares (47,154 to be exact<sup>30</sup>), so evidently the deposit extends to more than 40,000 hectares. As a result of promising samples taken in three salares (Caligüey, Santa Clara and La Salada), a sales company was formed, Litiomex S.A. de C.V., under the terms of an agreement with a group of Spanish investors associated with Banco Santander. These investors, we are informed, will have the rights to undertake the sale of the processed lithium.<sup>71</sup> Apparently, an initial payment of 2 million euros by the investors to Litiomex was agreed upon for 2010 and an additional three million between 2011 and 2012 as stipulated by the sales agreement. This intake of capital is essential since the cost of a pilot plant with a projected capacity to treat 1,000 tonnes of lithium containing raw material per day was estimated to be about five million dollars. Construction of the plant was scheduled to begin in 2011.<sup>27</sup> However, a note in the Express of San Luis Potosi states that apparently the full blown processing plant requiring an investment of some 200 million dollars would commence in 2012.<sup>16</sup>

Director Sutti Courtade is actively engaged enticing foreign firms to partake in the development of the deposit. However, he does apparently condition an alliance: The firm must commit itself to establishing a battery factory in the region of the salt pans.<sup>5</sup> Only time will tell if this in fact shall be. Sutti Courtade stated that the company LG had offered to build a battery plant in the region to supply HEVs<sup>27</sup>, but another news source quoted him as saying that the Chinese firm, Citic Guoan Group would be the one that installs a lithium battery plant in Santo Domingo, SLP. This large state-owned firm with lithium resources in Tibet would supposedly supply lithium-ion batteries for electric vehicles being made by

Nissan, Honda and GMC.<sup>71</sup> Additionally, it appears that Martin Sutti has been in talks to promote external financial participation not only with Chinese companies (Citic Guoan, plus Jien Nickel Inc. and the Horoc Group), but also with South Korean, Canadian, Australian and American companies. According to Sutti Courtade, a total of more than three million dollars for exploration has been offered by Jien Nickel, Horoc and the Australian company, Santa Fe Metals.<sup>27</sup> Not only this, he also affirmed that a large portion of the more than \$200 million needed to exploit the deposit would come from firms based in those countries.<sup>28</sup> This, unfortunately, has not been confirmed more recently. At any rate, besides the legal concessions in possession of Piero Sutti, Mr. Sutti added that his firm has obtained water and environmental licenses, the former from the Comisión Nacional de Agua and the latter from the Secretaría de Ambiente y Recursos Naturales (Semarnat). These are positive results, as is the fact that the 47,000 hectare concession tract has adequate transportation and electricity facilities nearby.

Now let's turn to information pertaining to lithium and potassium quantities and quality as expressed by grade. Perhaps it's not surprising that many mining exploration companies, in order to attract hard to garner capital to aid in exploring, mining and processing their mineral discoveries, tend to be, shall we benevolently say, extremely optimistic regarding the future potential of the mining property into which so much work has been invested. When the information available to the interested public is still scarce, dispersed and even sometimes contradictory, a solid assessment, especially from afar, is difficult. This is the bind I find myself in regarding the lithium-potassium deposit belonging to Piero Sutti S.A de C.V., although there are some hard data at hand. Let's begin with the information in Litiomex's web site ([www.litiomex.mx](http://www.litiomex.mx)).

First of all, I found a total of 7 concession titles including the number of hectares corresponding to each title, with Sutti-19 being the largest, comprising 22,309 hectares, the grand total being 47,154 hectares. Initial sampling of 20 salt pans (lagunas or salares in Spanish) was performed. It is stated that of the twenty lagoons, San José Caligüey, Santa Clara, Saldívar, La Colorada, Hernández and La Salada were notable for their high values (of lithium and potassium). Of these, there are no data included for Hernández, while there are data for lagoons not mentioned above. Within each concession title there is a list of lagoons with initial estimates of lithium carbonate and potassium chloride tonnage equivalents corresponding to "tested reserves", "inferred reserves and "possible reserves". No information dealing with these "reserve" categories is provided regarding sampling nor grades. It appears they are preliminary estimates. In truth, inferred reserves and possible reserves are not reserves but inferred resources and possible resources, which is far less certain than proven reserves. A question is what does Piero Sutti define as "tested reserves". Are they "proven reserves"? I suspect not. For example, the concession title Sutti-19 includes 5 lagoons. For each lagoon, a figure is given for the number of hectares explored. For the 5 lagoons, a total of 2,580 hectares were explored (though how thoroughly explored is not detailed). These 2,580 hectares explored represent about 11.6% of the 22,309 hectares corresponding to Sutti-19, which may be acceptable, but without more sampling data a serious evaluation is impossible. Not wishing to extend these comments, I'll only add that the 2,327,567 tonnes of lithium carbonate and 140,586,000 tonnes of KCl estimated for the concession title Sutti-19 are what probably should be called "total resources" or even "guesstimates", but certainly not "total reserves". We haven't the slightest idea of what grades and, even more, variation of grades are associated with this concession. Nor is there any data regarding evaporation rates, chemistry treatment

difficulties, the magnesium/lithium ratio, and a myriad of other characteristics of the deposit, though these proprietary data may be too much to ask for at this stage of the development of the deposit. Strange, too, are the same tonnage estimates of  $\text{Li}_2\text{CO}_3$  and KCl for Sutti 24, 25 and 26, in each case being 548,730 and 7,776,000 respectively for all three concessions. Not at all convincing! If we disregard for the moment the doubtful validity of this repetition and simply add up all the tonnages for Sutti-19 through Sutti-26, the total comes to 4,288,755 proven, inferred and possible lithium carbonate reserves (better stated as resources), and dividing by factor 5.32 to convert from  $\text{Li}_2\text{CO}_3$  to its Li equivalent, comes out to be a little more than the 800,000 tonnes of lithium that director Martin Sutti has said to be the least amount held in the deposits.<sup>17</sup> Needless to say, not all of this lithium content will be economically and technically extractable. Then, too, Jason Mick, the author of the Daily Tech article, adds that investors apparently “desire to stick with proven sources, such as those in Argentina and Chile”. Keith Evans, with disconcerting hyperbole, goes even further saying that “Chile and Argentina have sufficient reserves (meaning resources) for billions of years”.

Some useful data did appear on the Litiomex’s February 9, 2011 web site for Metallurgical Advances in which a Certification of Samples exists, but even here I could find no correspondence of these data for Lagoon Salada and Lagoon Caligüey with the former Concession Title data of the same lagoons. The differences cause a sensation of confusion and doubt. In the case of Lagoon Salada, for example, we are informed of 20 million tonnes of proven reserves of litio, 90 million for probable reserves and also 90 million for possible reserves. Again probable and possible reserves would be more conservatively classified as probable and possible resources. Why probable and possible tonnage resources are the same is not explained. What is shown clearly are the 711 samples taken from 151 holes, the result having been certified by the Inspectorate company based in Richmond, British Columbia. What is the result? An average grade of contained lithium is reported as 870 ppm (parts per million), which is stated as equivalent to 4,567.5 ppm of LCE (lithium carbonate equivalent).<sup>\*</sup> The average grade of potassium content reported is 3.25%, which means 32.5 kilos per tonne. The maps showing the individual samples for lithium and potassium are very illustrative of the sample variation grades, from very high grades to low ones, which greatly helps in designing the mining strategy. One could ask, regarding the sample maps associated with Lagoon Salada, what exactly the dimensions are. Are they 1,000 meters X 2,000 meters? They aren’t defined, unfortunately.

The only other spatial distribution of lithium and potassium values is that pertaining to salt pan number 2, Caligüey. The laboratory Asesoría en Absorción Atómica based in SLP performed the analysis of 924 samples taken from 194 holes. In this case, proven reserves have been estimated to be 22 million tonnes, with probable reserves of 110 million tonnes. Does this mean total reserves are 132 million tonnes or should this figure be interpreted as total possible resources, not necessarily all of which can be considered economically extractable at current prices and with standard technology? Howbeit, the average grade of contained lithium is reported as being 311 ppm, lower than at Lagoon La Salada, but still respectable depending upon other crucial characteristics of the deposit, some of which I mentioned before. These 311 ppm are stated as equivalent to 1,632.75 ppm LCE. As in the case of La Salada, Caligüey apparently resulted in an average potassium content grade of

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<sup>\*</sup> The factor used for converting from Li content to LCE is 5.25. If the periodic table is used, the more precise conversion factor is 5.32.

3.25%, whose coincidence surprised me and raised some personal doubts. Again I would ask if the dimensions of the sample maps are 1,800 meters X 1,300 meters. The question is not frivolous, since a sample area of this size is considerable and, therefore, important for mining. Once again, the variation shown of values for lithium and potassium is highly revealing and useful.

Martin Sutti stated that the analyses of five laboratories showed that “the quality of the deposits is greater than expected”, the high content of lithium having been confirmed by Process Research Associates Ltd. of Canada, Sumitomo Corporation of Japan and others located in the United States, Peru and one in Querétaro, the latter of whose names he doesn't mention.<sup>71</sup> Unfortunately, the empirical results of these analyses have not been divulged publicly. The two above analyses for Caligüey and La Salada jar with other statements of overall grades mentioned by the CEO of Piero Sutti. For example, according to the note published by the Latin American Herald Tribune, Martin Sutti said that the 40,000 hectare deposit could have a concentration of 750 grams of lithium per tonne (i.e., 750 ppm on average for all the deposits).<sup>28</sup> Another statement put the average between 600 and 900 ppm, as well as saying that Caligüey could show 832 ppm and not the 311 in the detailed analysis above.<sup>27</sup> This may not be realistic once other salt pans are sampled more thoroughly. But, it is true that the Silver Peak deposit in Nevada is still being economically exploited with a lithium content of less than 300 ppm, as Martin Sutti pointed out (actually about 230 ppm).

It should be stressed, in spite of the critical observations I have made, that the development and economically successful commercialization of these lithium deposits –a first for Mexico --as well as what could be the first potash mine with future beneficial substitution of potash imports, is only to be applauded. Other interested parties have been more critical. For example, in an article by Jonathan Ruiz in the April 9, 2010 edition of *Reforma*<sup>51</sup>, before the rather limited sample results mentioned above were made available, Rafael Alexandri Rionda, the director of the Servicio Geológico Mexicano, and Jon Hykawy of Byron Capital Markets, stated that the results shown by Piero Sutti, at least up to the time of the article, were an illusion and that, according to Mr. Rionda, an economic feasibility study is required; furthermore, that the project is only in an exploration phase. He also stated that it's a project that tries “to draw the attention of investors in order to keep on exploring and to find a way to meet production costs.” Mr. Hykawy additionally pointed out his belief that production costs would be higher than lithium carbonate market prices, evidently in contrast to what Martin Sutti had said about his production costs being less than the Chilean Salar de Atacama per unit costs, considered to be the least costly per tonne production in the world.<sup>27</sup>

Before ending this section, perhaps some mention of geological characteristics of the SLP/Zacatecas lithium deposits should be added, based on Litiomex's web site. The results of two samples analyzed by Sumitomo of Japan showed that the principal minerals were quartz, vermiculite and feldspar, the latter explaining the presence of potassium. An X-ray diffraction study also done in Japan identified the mineral illite, a mica-like clay found in argillaceous sediments, intermediate in composition and structure between muscovite and montmorillonite. Muscovite, a hydrous potassium aluminum silicate with chemical formula  $KAl_2(AlSi_3)O_{10}(OH)_2$ , would also explain the existence of potassium in the deposits. Montmorillonite is a hydrated sodium calcium aluminum silicate. An additional X-ray study of 5 samples from Santa Clara and Caligüey lagoons, performed by the Centro de Tecnología Avanzada, CIATEQ, in Querétaro, identified the lithium containing clay

mineral of the montmorillonite group, hectorite, whose composition is  $(\text{Mg,Li})_3\text{Si}_4\text{O}_{10}(\text{OH})_2$ . The hectorite is derived from the hydrothermal alteration of volcanic rocks, in this case the altered andesite found in the base of the sediments that fill, for example, the Caligüey lagoon. Geologist José de Jesus Parga tells us that there are outcrops of what locally is called “sinter”, an amorphous quartz known as chalcedony, in the Caligüey, Santa Clara and La Salada lagoons and that in much of the first two of these lagoons there are abundant fragments of this mineral. He adds that the existence of the “sinter”, that is, the chalcedony, proves that there were hydrothermal systems loaded with silica ( $\text{SiO}_2$ ) which, upon encountering the lagoon water, resulted in the deposition of the “sinter”. Furthermore, Geologist Parga points out that the inferred acidic hydrothermal fluids probably caused the argillaceous alteration of the andesite, thus accounting for the presence of the illite and hectorite.

## IX. CONCLUSIONS

An increasing preoccupation with oil (gasoline) dependency and environmental concerns has stimulated a rising trend in the production of vehicles powered by lithium-ion batteries, which portends also an ongoing greater demand for lithium. Although an intense debate ensued, some saying that lithium reserves are not sufficient to satisfy both conventional demand (for example, glass, ceramic and non-automotive lithium battery demand) and the exploding vehicular demand for lithium, I believe that reserves, production and supply should be adequate for the foreseeable future. Low cost continental brine deposits, the better hard-rock lithium containing pegmatites, Western U.S. hectorite deposits, the Salton Sea KGRA brine, some oil-field brines and the newly discovered Serbian Jadarite should be sufficient supply sources to meet the growing demand, though higher prices will need to be forthcoming to meet the higher costs inherent in some of these resources, other than the better continental brine sources of lithium. Exploration for lithium deposits has accelerated throughout the world, so new discoveries will be made and developed.

Chile and Argentina dominate in the production of lithium carbonate from their brines. Bolivia’s Salar de Uyuni is a huge promise for the future when and if the Bolivian government partners with international firms providing capital and know-how. China, though still producing lithium carbonate from imported and domestic spodumene concentrates, most likely will soon ramp up output from its remote Tibetan and far-western brines. However, most of its production of lithium and its compounds will probably be destined for China’s domestic market. Australia is the principal producer of concentrates from lithium containing pegmatites as well as the major exporter of high-grade concentrates. The United States remains the most important producer of downstream high value-added lithium compounds and is also the major importer of lithium carbonate, principally from Chile and Argentina.

The oligopolistic structure of the producer side of the lithium market is dominated by three large chemical companies from continental brines, the most important being SQM (Sociedad Química y Minera de Chile), followed by Chemetall Foote, now a subsidiary of Rockwood Holdings, and FMC (Foote Mineral Company), plus the Australian miner, Talison Minerals Pty Ltd., the dominant concentrate producer. Prices of lithium and its compounds are not established in international commodity markets, such as are the cases of copper and oil, but through proprietary contracts directly determined between seller and

buyer, which is to say there is no spot or future market, so that price information is difficult to come by.

Lithium-ion batteries to power HEVs, PHEVs and pure EVs are not, nor should be, the only object of present and future research efforts to power vehicles. Research in other battery chemistries is obviously important and should and will continue, for example, in Zn-air, Zebra (NaNiCl) and NaFeCl, capacitor technology, hydrogen-powered fuel cells, and fly wheel technology.<sup>58</sup> Then, too, efficiency improvements for internal combustion engines have been notable and will certainly deepen, since the use of gasoline will still be necessary for many years.<sup>4</sup> Nor is the switch from dependency on oil to dependency on lithium a wise and even viable geopolitical strategy. From the viewpoint of consumers, diversified and competing sources of lithium in many countries are better than a new dependency on only a few countries. Research into diversified battery technologies stimulates innovation, leads to more competition, and eventually to quality improvements and lower prices, besides greater geopolitical security, all good for consumers.

Regarding the particular lithium/potash brine deposit on the San Luis Potosi/Zacatecas border in Mexico, it can only be desired that a thorough feasibility study will lead as soon as possible to an economically viable operation.

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