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Production of Magnesium from Great Salt Lake, Utah, USA

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ABSTRACT

Magnesium metal has been commercially produced from the waters of Great Salt Lake since 1972. Worldwide use of magnesium has markedly increased over the last twenty years due to its unique properties of low density and high strength. Great Salt Lake is a valuable resource for the recovery of magnesium minerals due to its chemical composition, natural geography/climate and proximity to transportation and markets. US Magnesium LLC and its predecessors have overcome various technical challenges as well as political hurdles, climatic calamities and market uncertainties. This discussion will describe the extensive use of solar evaporation ponds to produce suitable raw materials for magnesium manufacture as well as significant mineral by-products. It will also include a basic technical description of the magnesium metal manufacturing process, an explanation of the operating history of the Rowley Utah plant, and briefly touch on the current commercial uses of magnesium metal.

INTRODUCTION AND HISTORY

Since the arrival of mountain man explorers in the 1830s and pioneer settlers in the 1840s, Great Salt Lake has been recognized as a valuable source of minerals. In addition to the sodium chloride “salt” implied by the name, the waters of the lake also serve as the raw material for the magnesium facility operated by US Magnesium LLC at Rowley, Utah. That facility currently accounts for all of primary magnesium production in North America and about 10% of the world’s magnesium metal production.

In 2006 the total world consumption of magnesium was estimated at about 8.0×10^5 metric tons. The plant at Rowley is among the largest in the world and represents about 10% of the world production and all of the current North American production in 2008.

The largest single use of magnesium is alloying aluminum to provide strength, malleability, and corrosion resistance. The aluminum beverage can is perhaps the largest single user, but significant quantities magnesium are present in almost every structural use of aluminum ranging from window frames to aircraft components.

The second most important market for magnesium is its use in structural applications via diecasting. The largest use of

magnesium die-castings is in the automotive industry where magnesium’s strength and lightweight are being used in an ever-increasing volume to improve fuel economy. Magnesium die-castings are also selected as a housing for many computer, cell phone, and electronic components because of magnesium’s electrical dampening properties. Another important use of magnesium die cast parts is in the manufacture of manual and power hand tools where magnesium’s lightweight improves safety and operator performance.

Magnesium’s electro-chemical potential is ideal for use in corrosion protection applications. A substantial amount of magnesium is consumed each year as high electrical potential sacrificial anodes, which are installed, for corrosion protection on oil, gas, and other pipelines, hot water heaters, and other equipment in need of cathodic protection.

Addition of magnesium to iron causes the iron to become higher strength and more ductile. Automotive crankcases, which used to be forgings, are now manufactured in ductile iron. The steel industry’s preferred method to remove embrittling sulfur compounds involves injecting powdered magnesium into molten metal so the sulfur can be removed as a slag.

Magnesium is also used as a reducing agent in the production of titanium, zirconium, hafnium, and beryllium. Other chemical uses of magnesium include production of Grignard reagent catalysts (a catalyst commonly used in the synthesis of halogenated organic chemicals) motor oil additives, pyrotechnic materials, and as a pharmaceutical material.

Production of magnesium metal from Great Salt Lake has roots from other places. In 1940, a diverse metallurgical company, National Lead Industries, began to develop technology for the production of magnesium by operating a United States government magnesium plant using the ferro-silicon process at Lucky, Ohio, during World War II. That company gained additional expertise in the production of magnesium metal in 1951 with the formation of a jointly owned company, the Titanium Metals Corporation of America (also known as Timet) at Henderson, Nevada. Magnesium metal is used as the chemical reducing agent in the production of titanium. The magnesium values are then recovered as $MgCl_2$, which is electrolyzed to recover and

recycle both magnesium and chlorine. In the early 1960s National Lead began an active investigation into the possibilities of producing and selling commercial quantities of magnesium metal. In searching for additional sources of magnesium, National Lead Industries joined with Hogle-Kearns, a Utah investment firm, and Kerr McGee, a diversified chemical company, in a venture to explore the potential of Great Salt Lake for producing magnesium metal. Acquiring rights to the lake's Stansbury Basin and its potential to be developed into an economically attractive solar pond system was the indispensable resource for the conceived operation. The Stansbury Basin is natural depression in the lakebed, which is bounded on three sides by natural terrain. The pond system as envisioned was bounded on the East by Stansbury Island, on the West by the Lakeside Mountain range, and on the South by naturally increasing contour (Figure 1). To the Northwest the envisioned solar ponds to large degree would be bounded by a mud flat that has higher in elevation than the majority of the basin. To the Northeast the distance between Badger Island and Stansbury Island was connected by a zone of relatively shallow water (Figure 1) that would facilitate the construction of an impoundment structure and still allow access to deep water that would assure a constant supply of feed brine for solar evaporation.

During 1965 and 1966, NL Industries conducted pilot operations to select the best process for use with Great Salt Lake brines. Scale model solar ponds were constructed at a location near to the proposed operation, and a manufacturing pilot plant for producing cell feed was built near Lakepoint, Utah, 45 km east of Rowley. Magnesium chloride product from this pilot plant fed a prototype cell at TIMET in Henderson, Nevada. From this program a decision was made in 1969 to build a magnesium plant at Rowley, Utah (Figure 1), utilizing brine from the Great Salt Lake. By the time construction plans were finalized, National Lead had acquired the equity of its partners and was the sole owner of the proposed magnesium operation.

Construction of the integrated facility began in 1970 with Ralph M. Parsons as the general contractor. The magnesium manufacturing plant was located on an undeveloped site 16 km north of Interstate 80 on the West side of the Stansbury Basin (Figure 1). The exact location was determined in part to take advantage of straddling power district boundaries that provided alternative sourcing of electricity which are a substantial component of the manufacturing cost. The plant site was named "Rowley" after Jeff Rowley who during the period of construction was the CEO of National Lead. In addition to normal construction costs, it was necessary to construct 24 km of paved highway, a railroad spur, a dedicated natural gas line,

and a dedicated 1.38×10^5 -Volt power line to service the new plant.

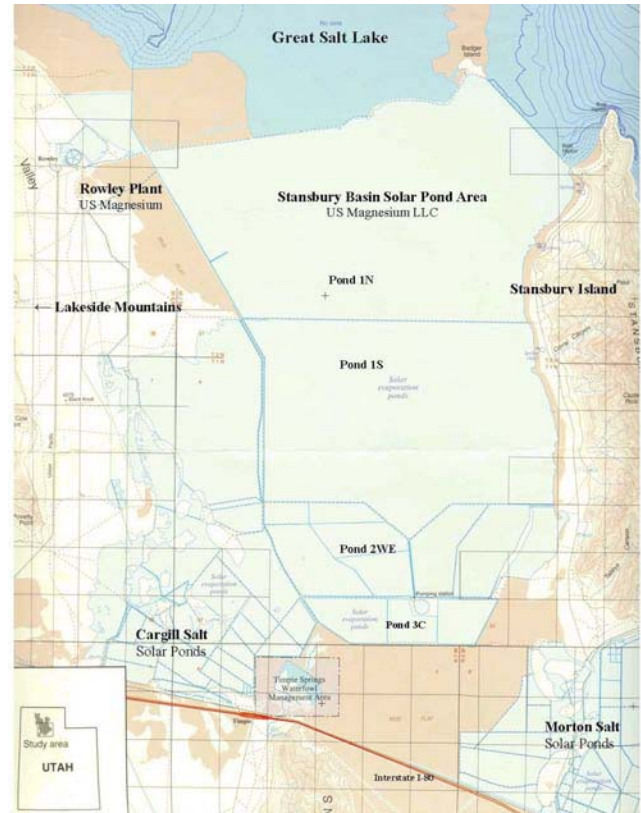


Figure 1—Stansbury Basin Solar Evaporation Ponds, Great Salt Lake, Utah.

Actual start up of the magnesium operations occurred in the summer of 1972. Initial start-up operations experienced substantial difficulties as viable operating systems were developed. It was necessary to shut down operations in 1975 to re-engineer some parts of the process. Norsk Hydro, a primary magnesium producer in Norway was contracted to assist this process. A system for the removal of boron was added to the process. Boron which is naturally occurring in the waters of Great Salt Lake had unexpected adverse implications for final magnesium product recovery and quality. Boron chemicals are surface active with liquid magnesium. If boron is not removed prior to electrolytic reduction of magnesium chloride, the surface of the magnesium metal produced tends to carry a film of chloride salts making the refining process more difficult.

Operations after the 1975 shut down approached routine, but suffered economically from the much higher than expected capitalization cost and lower than expected plant productivity. In 1980 NL Industries (National Lead changed its name to NL industries in the mid-70s) sold the magnesium operation to Amax Inc., a diversified mining and natural resource company.

Shortly after the transfer of ownership, a change in the weather pattern caused an unprecedented rise in the level of Great Salt Lake. Amax was compelled to expend millions of dollars to continue operation. Millions were spent to raise and fortify the dikes that separated the Stansbury Basin Ponds from Great Salt Lake (Figure 1). Additional expenditures were required to expand the solar evaporation area to compensate for wet weather patterns and the dilution of the mineral content of the lake caused by the increased volume. Modifications to the Rowley magnesium manufacturing process were made in an attempt to compensate for weaker than normal feed brines.

In spite of company efforts, a storm on June 7, 1986 coupled with record lake elevations, breached the main dividing dike that separated the solar ponds from the lake. Over the course of a week, the Stansbury Basin Ponds filled with lake water raising the level in the ponds by about 2.1 m (7 feet) and dropping the level in the balance of the lake by an estimated 14 cm (5.5 inches.)

Realization of the time required to bring the flooded Stansbury Basin ponds back into production, and uncertainty as to the future trend in lake levels, caused Amax to examine other alternatives. During this period, magnesium production continued at a reduced rate using brines purchased from Reilly Chemical near Wendover, Utah, located 150 km west on the Utah-Nevada state boundary and Leslie Salt located near San Francisco Bay, California.

It was determined after substantial analysis that there was an area 70 km to the west near the Knolls, Utah, comprised of mud flats interspersed with sand dunes that could be converted to solar ponds of an appropriate size at a reasonable economic cost, and at a speed of construction that could make use of Great Salt Lake brine in New Foundland Bay that was there as a result of the State of Utah's "West Desert Pumping Project". The permits to use the area of interest were obtained and construction with an expedited completion schedule commenced in May of 1987 with the engineering firm of Morrison-Knudsen acting as the general contractor. The construction included a 10 km feed canal, six pump stations, a maintenance shop and office facility and over 100 km of containment dikes. Construction was sufficiently completed by December of 1987 that the "Knolls Solar Evaporation Ponds" could start the initial filling. In addition to the construction of ponds at

Knolls, Amax also assisted the State of Utah in 1988 by extending the inlet canal to the Hogup Pump Station that provided suction head protection and capacity to the West Desert Pumping Project. This was accomplished with a large cutter-suction dredge, the Vagabond, which was then owned and operated by Amax.

The Knolls ponds were designed anticipating that the West Desert Pumping project would operate for a limited period. The operating plan at Knolls included sufficient storage that the ponds could supply and store up to 10 to 12 years of plant feed after pumping to the West Desert ceased. The West Desert Pumping Project operated into 1989 and then was shut down. Brine was generally accessible from New Foundland Bay until mid-1990. After that time brine would be available on occasion from re-dissolution of the salt deposited on the West Desert.

In 1989 Amax sold the magnesium facility to Renco Inc., a privately held company of New York. The magnesium operation was renamed Magnesium Corporation of America or "Magcorp."

In the late 1980s and early 1990s the level of Great Salt Lake receded as quickly as it had risen in the early 1980s. By 1992 the lake level had retreated to a level that allowed Magcorp to begin the process of re-commissioning the ponds in the Stansbury Basin. The first harvest brine in ten years from the Stansbury Basin ponds was brought in 1995. The Rowley magnesium operation has operated on raw materials brine produced in the Stansbury Basin solar ponds since that time.

In 2001 economic conditions led to Magcorp filing bankruptcy. In 2002 the Renco Group re-purchased the assets in a bankruptcy sale and a new company, US Magnesium LLC, was formed.

The Rowley Magnesium Process

Costs and reliability are both critical factors in any manufacturing process. The same is obviously true for magnesium operations at the Rowley plant. Decisions are made with the intent of reducing energy costs and maximizing equipment efficiency. The present Rowley process is described below.

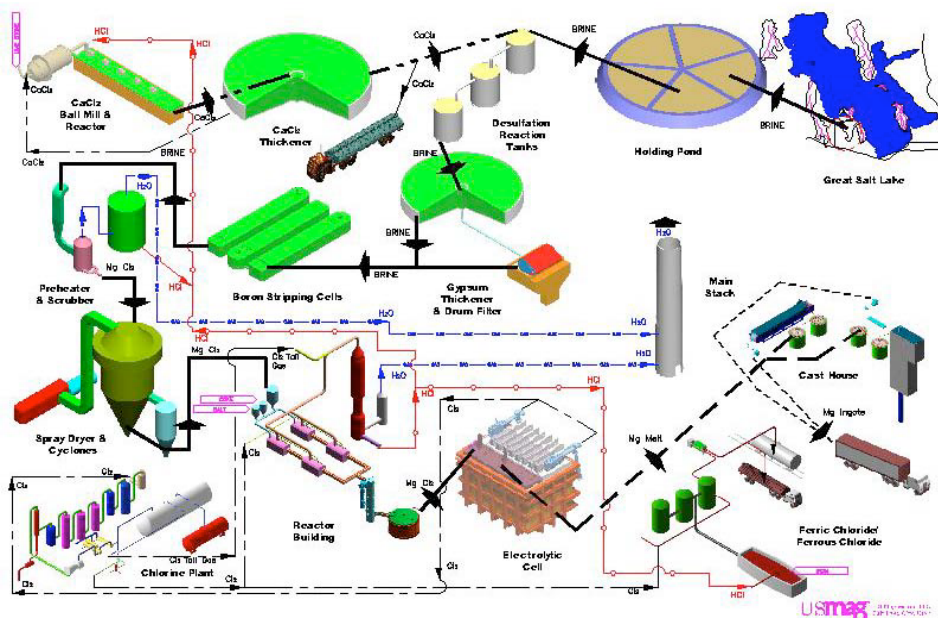


Figure 2—Simplified magnesium production process.

Solar Evaporation

The source of raw materials for the manufacture of magnesium is the magnesium chloride (MgCl_2) that occurs naturally in Great Salt Lake. The natural magnesium concentration in the South Arm of the lake has ranged as low 0.18% Mg in 1986 when the lake level was at its zenith, to approximately 1% at the lake's historic low level in 1963. The nominal concentration of magnesium is about 0.45% Mg by weight. To be an economically acceptable feed to the Rowley magnesium manufacturing process, a concentrated feed brine of greater than 8.4% Mg (by weight) is required. To achieve this concentration, US Magnesium employs the world's most extensive industrial use of solar energy. The Stansbury Basin ponds are comprised of State mineral leases that occupy approximately 300 km^2 (7.5×10^4 acres). The actual "wet area" within earthen dikes amounts to about 225 km^2 (5.6×10^4 acres). The Stansbury Basin ponds annually bring in between 75 and 135 billion liters of lake water dependent on the previous year's evaporative performance and inventory needs. The basin is divided into large pond segments. Efficient operation and maximum recovery is achieved by operating the ponds in a continuous mode where the brine advances like a slow moving river that becomes shallower as magnesium concentration increases rather than letting individual ponds evaporate to the desired concentration. The progressive concentration of magnesium is illustrated in Table 1, which shows the relative concentrations of Great Salt Lake and the effluent from three of the ponds in sequence. The magnitude of this evaporation step is illustrated by the fact that less than one

percent of the volume of the original Great Salt Lake brine finally reaches the plant for manufacture of magnesium. In concentrating the brine, about five million metric tons of salts are deposited in the ponds each year.

Table 1—Weight percent of each constituent.

	Great Salt Lake brine	Effluent Pond 1S	Effluent pond no. 2WE	Effluent pond no. 3C to holding pond
Mg	0.4500	2.000	4.800	8.50
K	0.3000	1.500	3.600	0.15
Na	4.0000	7.000	2.600	0.20
Li	0.0020	0.010	0.024	0.07
B	0.0018	0.009	0.021	0.06
Cl	7.0000	14.000	16.000	22.60
SO_4	1.0000	5.000	5.300	4.20

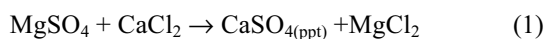
Because of the seasonal variations in weather and temperature in Utah, and because the rate of evaporation is inversely related to the concentration of the brine, it is only possible to achieve the desired final brine concentration in the two or three hottest and driest months of the year typically starting in the month of June and continuing through early September. When the target magnesium concentration is achieved, the concentrated brine is pumped to "deep storage" holding ponds, which in aggregate can store up to three years supply of brine. This deep storage is required to avoid the dilution from annual precipitation and

to assure an adequate supply of plant feed brine during years when weather conditions won't permit adequate evaporation/concentration success. In addition to the magnesium rich brine product that serves as the feedstock to the magnesium operation, sodium chloride and potassium salts are also recovered and sold as will be described later.

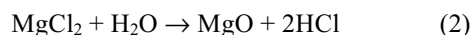
Feed Preparation

The preparation of the magnesium chloride contained in the concentrated lake brine for use as feed for electrolytic cells entails the removal of unwanted impurities, further concentrating the brine, and eliminating water. In the final steps the $MgCl_2$ is melted and purified. The process steps are outlined in Figure 2.

The concentrated magnesium chloride brine is pumped into the production plant from the deep storage holding ponds to a series of reaction tanks where $CaCl_2$ is added and gypsum is precipitated and collected in a thickener. This reaction may be simplified as follows:



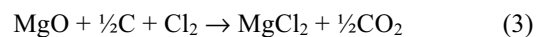
This step removes most of the sulfate, which may be unstable (explosive reactions) in molten systems. The brine next passes through a solvent extraction (liquid-liquid) step where a long chain alcohol in a kerosene carrier is used to remove the naturally occurring boron from the solution. The active reagent used has varied through the life of the magnesium operation, but decanol [$C_{10}H_{19}OH$] and octanol [$C_8H_{17}OH$] have been used with good economic performance. This impurity that is "surface active" on molten magnesium surfaces must be removed as it adversely affects the magnesium recovery purity of the final product. Next, the brine passes through a preheater vessel, which utilizes available waste heat to further concentrate the brine prior to being fed to spray dryers. The spray dryers convert the concentrated brine to a dry $MgCl_2$ powder. The intent is to remove all of the water, but some residual amount remains. Additionally some of the magnesium chloride is oxidized to a magnesium oxide [$Mg(OH)_xCl$] in the drying process. For simplicity this group of chemical species, magnesium hydroxy-chloride is generally referred to as MgO . This MgO is formed by hydrolysis of $MgCl_2$ as shown in a simplified way as:



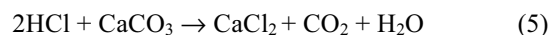
The spray drying process is energized by the exhaust gases from natural gas fired turbine/generators in a true utilization of co-generation technology. The electricity produced is used in the electrolysis of magnesium chloride described later. Gas burners are also available to operate the spray dryer when the turbines are not available for use.

The spray-dried powder is pneumatically conveyed and stored in large bins until it is fed to the cell feed preparation step that is locally referred to as the "Reactor" process. In the Reactor, the powder produced in the spray dryers is melted and further purified with chlorine and carbon to remove MgO and water. This is a continuous process where the spray dried magnesium chloride powder is first fed into a brick lined furnace known as a "melt cell" where it is melted via electrical resistance heating. The molten salt then overflows from the melt cell through a ceramic lined trough into a "reactor cell" where additional retention is provided to bring the intended chemical reactions to completion. A tertiary chlorine treatment step uses proprietary contact technology to further reduce the magnesium oxide content. The refined/purified molten salt moves to holding cells where the temperature is kept at $900^\circ C$ (1550 EF). From the holding cells the purified molten salt is transported to the electrolytic cells by custom designed mobile molten material haulers.

Removal of impurities from the molten salt is complex but can be summarized by the following simplified equations:



HCl produced from the chlorination of water as shown in Equation 4 is recovered as concentrated, but not commercial grade hydrochloric acid which is subsequently reacted with limestone to produce $CaCl_2$ (see Equation 5) needed for desulfation and in the production of iron chlorides which are sold as byproducts.



Production and Handling of Magnesium Metal

Molten salt containing about 94% $MgCl_2$ is transferred to the electrolytic cells on a regular schedule. At the time of construction in 1972, the electrolytic cells at Rowley (1999) were essentially a modification of the I.G. Farben cell developed in Germany in the 1930s. Cells of this design

were also referred to as cooled cells or I.G. cells. Those cells consisted of five graphite anodes with steel cathodes on either side. Semiwalls (thin ceramic diaphragms) extended from the top of the cell down into the bath isolating chlorine gas from the molten magnesium. The gas compartments around the anode collected the chlorine gas, which was generated on the anode surface. The chlorine is drawn to the chlorine recovery plant. The cathode compartment collects the magnesium metal, which floats on the surface of the molten salt due to its lower density (sufficient air is passed over the cathode compartment to remove any fumes and then through a scrubber in order to provide a fume-free environment for workers). In addition to the cooled cells, US Magnesium also utilized "Amax Sealed Cells" which were a diaphragmless (no semiwall) design developed under the period of Amax's ownership. These sealed cells had a single large common anode compartment and the molten magnesium is directed to a different compartment where it may be removed. The magnesium metal is removed from the cells and is sent to the foundry.

Beginning in 1995 the magnesium operation engaged in a research and development effort to modernize the design. The intent was to improve electrical efficiency, magnesium recovery and to reduce operational costs and environmental air emissions. The design developed over a six-years and eventually was named the "M-Cell" design. The first commercial M-cells were installed in April 2001. By late 2002 all other electrolytic cells were replaced by M-cells.

Efficient operation of electrolytic cells depends on maintaining temperatures and magnesium concentrations. The geometry of the M-cells physically separates the molten metal formed on the cathodes from the chlorine gas that is generated on the anode surface. Electrolytic cells frequently receive input of molten magnesium chloride from the Reactor process in order to maintain optimum operation. Magnesium metal being less dense than the molten salt electrolyte floats to the surface where it is collected by mobile vacuum equipment. In addition to magnesium chloride, the electrolytic cell electrolyte also contains sodium, potassium, calcium and lithium chlorides that are derived from the raw materials and process additions of calcium. If the magnesium concentration is sufficiently depleted, production of sodium metal commences. The electrolytic decomposition of magnesium chloride is otherwise straightforward.

The collected molten magnesium metal is transferred to the foundry via mobile transports referred to as "Glamas" or vacuum wagons that utilize a stationary vacuum system to draw molten metal from the cell surfaces into an appropriate steel vessel. Air pressure is subsequently applied to evacuate the molten magnesium to holding/refining furnaces where it is refined and/or alloyed as required. The molten magnesium is then cast into shapes appropriate for the customer's needs. These molds may vary from as small as 7 kg (15 pounds) to as large as 800 kg (1750 pounds). Most magnesium shipments to customers are conveyed by truck with a lesser portion being shipped by rail.

By-products of Magnesium Production

In addition to manufacturing magnesium metal, US Magnesium also produces and sells a number of byproducts. A co-product of electrolytic magnesium is chlorine. Approximately three kg of chlorine are produced for each kg of magnesium. US Magnesium accounts for about 1% of the United States' chlorine production. Part of the chlorine produced at US Magnesium's Rowley operation is recycled into the described "Reactor" process. The balance of the chlorine is loaded into tank cars, transported by rail and sold as merchant grade chlorine. Before the modernization of the electrolytic process in 2001, the capture of chlorine at the Rowley facility ranged around 85%. With the advent of the modernization of the electrolytic process essentially all (99.9%) of the chlorine is captured as elemental chlorine or converted to hydrogen chloride and captured in scrubbing equipment. Chlorine has a variety of chemical uses and is also used in water purification. The chlorine produced at Rowley has largely been used in the production of ferric chloride, production of plastics, leaching of gold bearing minerals, and other general commercial uses.

As previously mentioned, US Magnesium produces calcium chloride using crushed limestone (previously oolitic sand) and hydrochloric acid produced in environmental control equipment (refer to Equation 5). One third of the calcium chloride produced is used in the process for the removal of sulfate from the solar pond brines. The balance is available for outside sales. Calcium chloride is used as an additive for specialized concrete, as a dust suppressant, and for heavy media purposes in oil field service.

Iron chlorides (ferrous and ferric chloride) are also produced for outside sales at US Magnesium's Rowley facility. The by-product hydrochloric acid is reacted with a variety of economically acceptable metallic iron sources to produce ferrous chloride. Ferrous chloride can be treated with chlorine to convert it to ferric chloride. These iron chlorides are sold and are principally employed as flocculating aids and odor control agents in sewage water treatment.

In the solar ponding operation a significant amount of sodium chloride salt is precipitated. Much of this is not commercially useful due to and remoteness from market locations or high content of potassium, magnesium, and sulfate. By contractual arrangement, about 25% of total brine volume in the solar pond system is diverted to an adjacent sodium chloride operation (Cargill Salt) (Figure 1) where sodium chloride is deposited in such a way that allows recovery of high quality commercial grades of NaCl. The bitterns (concentrated brines exiting the sodium chloride operation) are then returned to US Magnesium for further evaporation and inclusion with the brine used for the production of magnesium metal. Additionally US Magnesium on occasion sells raw sodium chloride salts from its pond floor when commercial opportunities occur.

As the brine approaches the final desired magnesium concentrations, the salts being precipitated from the saturated solution are composed predominately of mixtures of potassium, magnesium and sulfate. The salts deposited in the final ponds are acceptable as feed for the commercial

production of potash fertilizer. The salts in the floors of these final ponds on occasion are harvested and sold for that purpose.

The magnesium chloride solution that serves as a raw material for magnesium production is also in demand as a custom ice preventative for road and bridge surfaces. It is also a suitable dust control agent. When inventories permit, US Magnesium sells excess magnesium chloride solutions for use in those markets.

Other by-products presently being considered from the production of magnesium at Rowley, Utah include commercial grades of hydrochloric acid (HCl), lithium metal or lithium compounds, and bromine compounds.

SUMMARY

US Magnesium and its predecessors have been successfully and economically producing magnesium metal from raw materials derived from solar evaporated brine solutions for more than 30 years. Such raw materials have advantages of low impurities and allow for a high volume manufacturing process that is energy and labor efficient. Such raw materials derived solutions also have low levels heavy metal impurities compared to mined magnesium ores. To generate metal from solutions requires multiple steps of beneficiation and purification to complete the transformation of magnesium chloride to magnesium metal. Perfecting the manufacturing process required years of development and optimization.