

Production of Magnesium and Aluminum-Magnesium Alloys from Recycled Secondary Aluminum Scrap Melts

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An experimental proof of concept was demonstrated for a patent-pending and trademark-pending RE12TM process for extracting a desired amount of Mg from recycled scrap secondary Al melts. Mg was extracted by electrorefining, producing a Mg product suitable as a Mg alloying hardener additive to primary-grade Al alloys. This efficient electrorefining process operates at high current efficiency, high Mg recovery and low energy consumption. The Mg electrorefining product can meet all the impurity specifications with subsequent melt treatment for removing alkali contaminants. All technical results obtained in the RE12TM project indicate that the electrorefining process for extraction of Mg from Al melt is technically feasible. A techno-economic analysis indicates high potential profitability for applications in Al foundry alloys as well as beverage—can and automotive—sheet alloys. The combination of technical feasibility and potential market profitability completes a successful proof of concept. This economical, environmentally-friendly and chlorine-free RE12TM process could be disruptive and transformational for the Mg production industry by enabling the recycling of 30,000 tonnes of primary-quality Mg annually.

INTRODUCTION

SINTEF at the Norwegian University of Science and Technology (NTNU) orchestrated an International Al Recycling Workshop (June 9–11, 2013) of 30 internationally recognized Al recycling experts in Trondheim, Norway.¹ These experts assigned highest priority to the development of a non-chlorine environmentally friendly de-magging process for recovering Mg from Mg-bearing Al scrap.

The purpose of this paper is to document proof of concept experimental results of the RE12TM process in a laboratory-scale electrorefining cell designed to recover Mg from secondary Al-alloy melts sourced from domestic Al alloy scrap feedstock and to produce primary-quality Al-Mg alloys.

North America produces only ~70,000 tonnes of primary Mg annually. The only practical recycling of post-consumer Mg is as alloying content in the Al-alloy recycling system. However, in that system, over 30,000 tonnes of Mg content is chlorinated or fluxed out of Al to end up as Mg chloride contamination of dross.^{1–11}

While there are technically feasible ways to sort out Mg-alloy particles from Al scrap shred, this is still not widely practiced due to the still low concentration of Mg alloys in Al shred streams.

Electrorefining is a well-understood, commercial way of purifying and separating and recovering metals.^{2–6} In most current commercial applications—for example Al, Cu and precious metals—it is the majority parent element that is refined out of the impure alloy. In the case of Mg-containing Al melt, Mg is more reactive than Al, allowing Mg to be oxidized at the anode surface and to be reduced back to Mg at the cathode. Since only a small proportion of the original Al melt is electrolyzed, this results in a very energy-efficient process of purifying Al and recovering Mg.

No results on commercially extracted Mg from molten Al-Mg scrap recovered for recycling have been reported in the literature. However, a similar concept has been proposed for recovery of Li from Al-Li aerospace scrap,^{7,8} but it is not yet developed or commercialized. In the past, Reynolds Aluminum had explored the electrorefining of Mg in their

laboratories, but that knowledge remained locked up in their internal reports and disappeared with the company. There are no papers in the open literature on the electrorefining of Mg from Al-Mg melts.

An experimental proof of concept was demonstrated for a patent-pending¹² and trademark-pending¹³ RE12™ process for a Mg recovery process.

The project was funded by the United States Department of Energy Advanced Research Project Agency (ARPA-e).¹⁴

Scrap-based alloys suitable for RE12™ treatment and the products to market were selected. The scrap, processor and customer supply-and-demand-chain needs, and quantities required were mapped out.

The composition of the electrolytes for the electrorefining cells was established. The composition was selected using the best available tools—literature information, thermodynamic databases, computational models, and the commercially available FactSage software program for the thermodynamic and phase diagram calculations. The research team prepared and characterized the electrolyte composition required for the electrorefiner, and demonstrated that the electrolyte composition can be maintained and cleaned of oxide contamination.

An industrial-scale Mg recovery electrorefiner, including internal components and a process for integrating it into a secondary Al smelter, was conceptually designed. A series of laboratory electrorefining cells that demonstrated the key technical aspects of the electrorefining process were constructed.

The refining cell performance was characterized and the optimum electrorefining configurations that resulted in a stable operation well below the target specific energy consumption of <10 kWh/kg Mg were determined. A series of electrorefining experiments designed to measure key process operating parameters and milestone metrics were successfully conducted completing the proof of concept.

The RE12™ process discussed in this paper is important to recycling of both new and old Al alloy scrap, in which Mg content typically on melting exceeds the target product composition limits. In the U.S., 30 kt of Mg is chlorinated out of Al foundry alloys. Additionally, 700 kt of recycled beverage cans and 60kt of automotive sheet mixed—alloy scrap are diluted with expensive and energy-intensive prime Al to reduce Mg concentration to the sheet product specifications. These are large market segments, and the introduction of the RE12™ process has the potential to significantly and positively disrupt the secondary Al smelting industry worldwide.

PROCESS CONCEPT

The process concept for extraction of Mg from Al scrap was designed to fit with existing Al remelting and recycling processes. Al is typically resmelted in

a sidewall reverberatory furnace and the Mg is chlorinated out of the melt by continuous injection of Cl₂ gas through the circulation pump impeller throughout the melting cycle. In this conventional system, continuous chlorination ensures that the Mg concentration in the metal heel in the furnace is always maintained at the product specification concentration. In the RE12™ process, Cl₂ injection and Mg chlorination is replaced by Mg electrorefining and Mg recovery for recycling. The melt from the melting furnace sidewall is continuously recirculated through the electrorefining cell, always maintaining the Mg concentration at the product specification level. The excess Mg present in the scrap feed is extracted and collected as Mg with very minor Al content.

Magnesium is removed from the electrorefiner as a continuously cast solid rod, thus avoiding problems of handling and protecting molten Mg from oxidation. The Al product is on specification and follows existing melt treatment and casting procedures. The Mg solid rod product is ready for sale as an Mg addition for Al-Mg alloys. Alloy melts, batched from prime Al, are always treated for removal of alkali and alkaline earth contaminants (Na and Ca). This standard treatment will also deal with any residual LiF or Li content of the Mg hardener product. Figures 1 and 2 illustrate the RE12™ process concept and its conceptual integration with an Al melter in an Al secondary smelter.

EXPERIMENTAL

Electrolyte Selection

Electrolyte composition was selected based on both thermodynamic calculations using the FactSage thermodynamic database and free-energy minimization software that calculates phase diagrams and chemical equilibria.

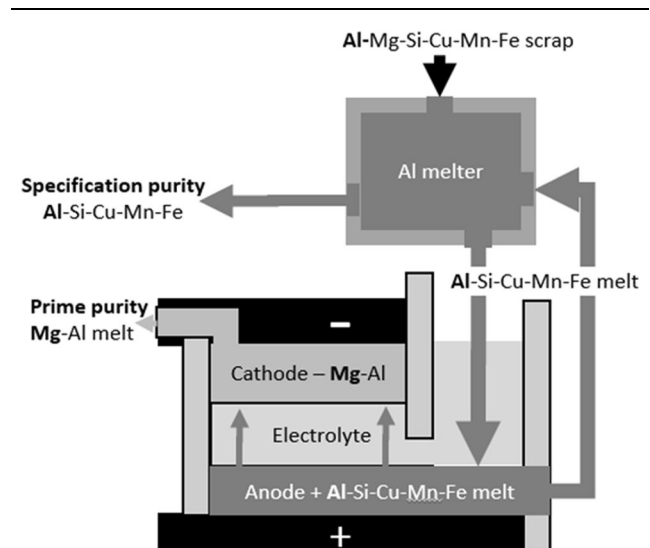


Fig. 1. Concept of Mg electrorefiner linked to Al scrap.

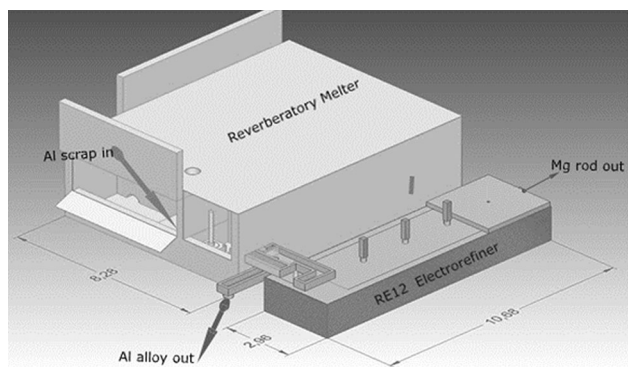


Fig. 2. Commercial concept. Integration of RE12™ electrorefiner with reverberatory melter (dimensions in meters).

Laboratory experiments were selected that best meet the following criteria:

- Melt density at 800°C: $\sim 2.05 \text{ g/cm}^3$
- Ability to transport both Mg^{++} and Al^{++} ions and electrodeposit them as metal on the cathode
- Maximum ionic conductivity
- Transport numbers: ionic 100%; electronic: 0%
- Minimum susceptibility to hydrolysis
- Chemical compatibility with materials of construction

Laboratory Cell for Electrorefining of Mg from Al-Mg Alloy Melt

A series of Mg cylindrical electrorefining cells were designed and constructed to demonstrate key aspects of the RE12™ process. The cells were all housed in an airtight stainless steel shell externally electrical-resistance heated to 700–900°C. The shell was evacuated, backfilled and then purged with Ar gas throughout electrorefining. Clean, dry molten electrolyte was prepared by pre-drying electrolyte components at $> 500^\circ\text{C}$, batching the electrolyte composition and pre-melting the electrolyte. Residual moisture was eliminated from the molten electrolyte by reduction oxidation (REDOX) reaction with Al or Mg added to the salt: $\text{H}_2\text{O}_{(\text{electrolyte})} + \text{Al}_{(l)} \rightarrow \text{H}_{2(g)} + \text{Al}_2\text{O}_{3(s)}$. Clean, dry solid electrolyte was loaded into the electrorefiner together with the starting Al-alloy pool and melted. In most cases, the cathode was then lowered into the electrolyte and direct current (DC) current was passed between the cathode and the anode. Cell temperature and voltage were measured by “K” type thermocouples and the outer sheath of the thermocouples acted as the voltage probe leads (Fig. 3).

The Al-anode metal pool was sampled periodically during the electrorefining run by sucking out $\sim 1 \text{ ml}$ of the metal liquid into a Ti tube with a syringe, and splat casting it on a cold steel plate. For precise analysis, the samples were quenched and then dissolved in acid for spectroscopic analysis with an inductively coupled plasma optical emission spectrometer, ICP-OES.

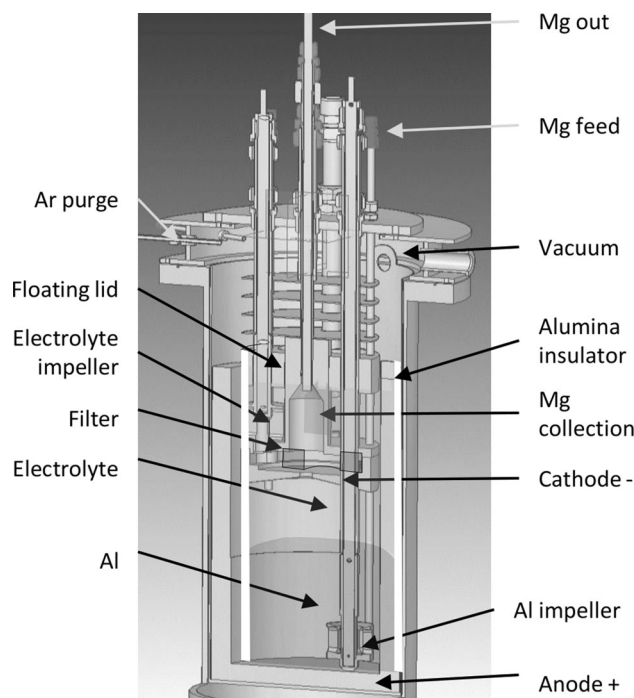


Fig. 3. Laboratory electrorefining cell: schematic of the version that included provisions for independent circulation of the electrolyte and the metal, and for filtration of Mg product droplets out of the electrolyte and their collection in a cavity in the carbon cathode block.

The electrolyte was also sampled periodically during the electrorefining run by inserting a cold Ti rod into the electrolyte and letting some of it solidify on the rod. The amount of Mg produced during the laboratory electrorefining runs was small so it was not possible to sample it periodically during the laboratory runs. Mg was recovered from the cell during the post-mortem. The quantity of Mg metal produced was evaluated by two methods. First, by dissolving the Mg deposited on the cathode in HCl and measuring the quantity of H_2 gas evolved, and later by weighing the cathode and the deposited metal and subtracting the original cathode weight.

In the last experimental run, which included a voltage probe, the electrical potential as a function of the vertical position in the anode-cathode gap was measured. This measurement allowed the determining of the voltage gradient in the anode-cathode distance, and calculating the conductivity of the electrolyte, and estimating the polarization potentials at the electrodes.

These measurements allowed the calculation of key process metrics such as specific energy consumption and efficiencies of extraction of Mg from the anode melt and of its deposition on the cathode. Reduction in the specific energy consumption in comparison with the conventional primary-Mg production routes allowed an estimation of the reduction in greenhouse gas emissions for Mg production.

Feed Material Used

The Al-alloy melt contained Mg, Mn, Si, Cu, Fe and Zn in concentrations that in various tests corresponded to several product alloy target specifications (foundry alloys: 10% Si, 3% Cu, 1% Zn, 1% Fe; for can-body alloys: 0.3% Cu, 0.3% Zn, 1% Mn, 0.8% Fe; and for auto-body alloys: 0.7% Cu, 0.5% Mn, 0.8% Si, 0.4% Fe). The process objective was to bring the Mg content of the electrorefined Al product to less than 0.1%, 1% and 0.75% respectively for foundry, can-body and auto-body alloys.

RESULTS

Electrolyte Selection

The electrolyte compositions were selected to best meet the following criteria:

Melt Density

To separate the Al—feed melt from Mg—product melt by density, the electrolyte should have a density half-way between the Al and Mg melt at an operating temperature of $\sim 800^\circ\text{C}$: Al- 2.3 g/cm^3 , Mg- 1.6 g/cm^3 gives $\sim 2\text{ g/cm}^3$ for electrolyte. For fluorides, only binary LiF-MgF₂ mixtures could achieve the target melt density while maintaining sufficient Mg²⁺ concentration for efficient Mg²⁺ supply at the cathode.

Ion Transport and Electrode Potentials

Fluoride salt mixtures of alkali and alkaline earth elements are able to transport both Mg⁺⁺ and Al⁺⁺⁺ ions and electrodeposit them as Mg metal on the cathode. The Mg alloying element has the highest electrode potential in the anode metal pool so it is the first metal to be oxidized at the anode and transferred to the electrolyte. Any Li contamination of the Al-Mg anode melt pool resulting from the $3\text{LiF} + \text{Al} \rightarrow 3\text{Li} + \text{AlF}_3$ or $2\text{LiF} + \text{Mg} \rightarrow 2\text{Li} + \text{MgF}_2$ salt-metal equilibria is oxidized at the anode before Mg extraction. The anode Al has the next highest electrode potential; hence, once Mg depletes from the anode surface, Al is next to be oxidized and transferred to the electrolyte.

Conversely at the cathode, Mg²⁺ must have the lowest electrode potential of the ion components of the electrolyte in order for the Mg to be deposited first at the cathode. Al³⁺ has a lower electrode potential and any Al oxidized at the anode, can be transported to the cathode and be deposited in the cathode pool in preference to Mg.

Ionic Conductivity: Maximum

Li⁺ is the smallest metallic cation with the highest mobility, and Li metal atom has the lowest solubility in both chloride and fluoride salts. This provides the selected LiF-MgF₂ fluoride electrolyte

composition with the highest ionic conductivity and the lowest electronic transport number, leading to a predicted current efficiency of $>99\%$.

Transport Numbers: Ionic 100%; Electronic: 0%

The very high current efficiency demonstrated in the electrorefining experiments indicates that ions (mainly Li⁺) carry virtually all the electrical current through the electrolyte and that the contribution of electron conduction is negligible for the LiF-MgF₂ electrolyte system.

Minimum Susceptibility to Hydrolysis

Thermodynamic equilibrium calculations indicate that the selected LiF-MgF₂ fluoride electrolyte composition is stable in contact with moist air at the cell operating temperature. This will allow operation of non-hermetically sealed industrial cells.

Electrolyte—dried and batched and pre-melted as described above in the experimental section—still reacted visibly with the Al-Mg anode alloy melt evolving H₂ gas bubbles and precipitating solid oxide particles.

The mass balance on the metal and the electrolyte quantity and composition indicated that, even after melting, the electrolyte still contained $\sim 5\text{ wt.}\%$ H₂O, presumably still complexed with MgF₂. That water had to be eliminated before Mg electrorefining could commence. A preliminary experiment indicated that cleanup by pre-electrolysis of $\text{H}_2\text{O} + \frac{1}{2}\text{C} \rightarrow \text{H}_{2(-)} + \frac{1}{2}\text{CO}_{2(+)}$ may be an efficient way to pre-clean the water from the electrolyte. However, for most of the experimental electrorefining runs, the REDOX reaction with the molten metal was employed for drying the melt. Resultant solid oxide particle contamination of the electrolyte observed during the cell post-mortem did not significantly interfere with the electrorefining process. The best results were obtained by re-freezing the electrolyte after REDOX cleaning, and separating clean white electrolyte from the oxide sludge, and using the clean, dry electrolyte.

Chemical Compatibility with Materials of Construction

LiF-MgF₂ is compatible with Al₂O₃, MgO, AlN, C, Ti and TiB₂. This gave a suite of materials for the construction of the laboratory proof-of-concept electrorefiner. CaO reacts with the electrolyte producing CaF₂, eliminating the Ca-aluminate-bonded refractories as potential materials of construction. At 800°C , LiF-MgF₂ has a superheat of $\sim 10^\circ\text{C}$, making it compatible with electrolyte containment by its own freeze in a full-scale electrorefiner. The preferred refractory is AlN, but Al₂O₃ is also compatible in contact with the Al-anode metal pool and MgO is compatible with both electrolyte and the Mg-rich cathode pool.

Electrorefining Experiments

The following is a selection of the most significant results from the electrorefining runs (Table I).

Qualitative Observations

High ionic conductivity of the LiF-MgF₂ electrolyte allows cell operation at high current densities. Stable electrorefining at current densities of up to 3.5 A/cm² with 100-cm² electrodes was tested and demonstrated in laboratory tests. Cell voltage under steady state is constant over time.

Electrolyte composition is stable over time at the laboratory time scale. Small pickup of Li by the metal products implies that under industrial steady-state conditions, small additions of Li⁺ will be necessary to keep the electrolyte composition stable indefinitely.

Table I. Laboratory cell parameters

Electrolyte	Based on LiF-MgF ₂ system
Inter-electrode distance (cm)	8
Nominal cathode electrode area (cm ²)	50–300
Cathode material	graphite or steel
Anode crucible material	graphite
High temperature electrical insulator	> 99.5% alpha alumina
Current density (A/cm ²)	1–3.5
Cell current (A)	50–300
Cell voltage (V)	1–3

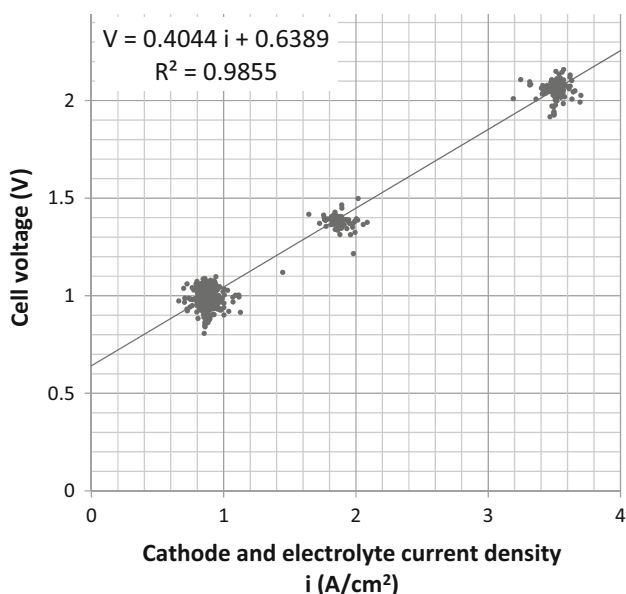


Fig. 4. Cell voltage as a function of current density.

Mg electrorefining product can meet all the impurity specifications with subsequent melt treatment for removing alkali contaminants.

Quantitative Electrorefining Results

Figure 4 illustrates the dependence of the cell voltage measured between the cathode rod and the graphite crucible containing the anode melt. The measured voltage is quite stable at each of the three current density groupings, with the range of the voltage variation at ±~0.1 V at each current density over the entire 6-h electrorefining run. High current densities of up to 3.5 A/cm² were demonstrated for Mg electrorefining, which are significantly higher than those in commercial electrolytic reduction of Al or Mg. Low electrode over potentials and high electrolyte conductivity permit operation at 3.5 A/cm² while still maintaining the internal cell voltage drop at ~2 V. This corresponds to an internal specific energy consumption of ~5 kWh/kg of Mg, and, if the cell is extracting 1% Mg from the Al melt, this also corresponds to 0.05 kWh/kg of Al.

Figure 5 illustrates the evolution of Mg concentration in the anode pool over the duration of the ~6-h electrorefining run, during which the Al metal was periodically sampled and Mg alloy was added to maintain Mg concentration at ~1.5 wt.%. The electrical charge passed through the cell and based on the charge were continuously measured to calculate the amount of Mg that would be extracted at a given current efficiency. The calculation fitted the measurements best with a current efficiency value of 100%. In an earlier electrorefining run with no Mg addition, a current efficiency of 97% was calculated.

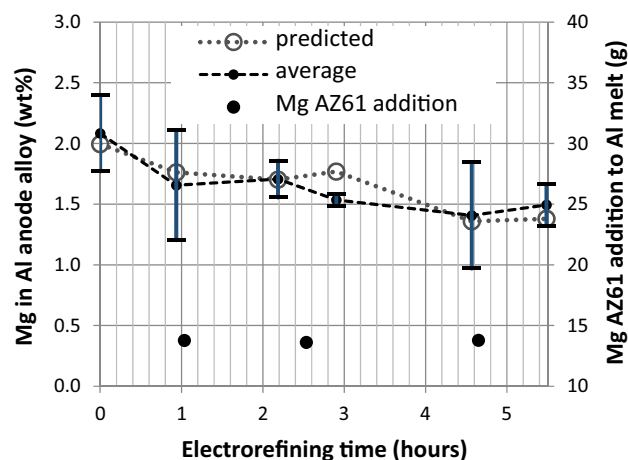


Fig. 5. Comparison, as a function of time, of the measured Mg concentration in Al-anode alloy with the predicted value based on 100% current efficiency for the process operating at the following steady-state conditions: electrolyte temperature 828°C, cathode and electrolyte current density 0.9 A/cm² and cell voltage 1 V.

Chemical composition stability of the electrolyte over time is a potential concern. To address this issue, electrolyte over the 6-h electrorefining time was periodically sampled.

Energy dispersive x-ray (SEM-EDX) measurements were used to demonstrate the composition stability. Since Li is not detected by EDX, the ratio of Mg/F x-ray intensity ratio as a function of time was followed.

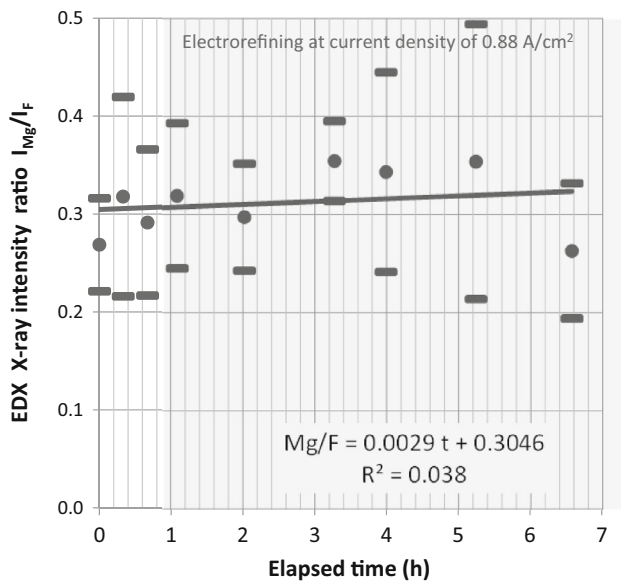


Fig. 6. Electrolyte chemical composition stability over time as measured by the EDX x-ray intensity ratio I_{Mg}/I_F .

Stability of the Mg/F ratio indicates that the Mg deposited at the cathode is replaced one for one by Mg extracted from the anode pool. Li losses are too small to affect the electrolyte composition over the time frame of a laboratory electrorefining run.

Figure 6 shows that there is no statistically significant change in the MgF_2/LiF ratio in the electrolyte during the electrorefining. There is a slight increase in the x-ray intensity ratio, and the I_{Mg}/I_F measurement is consistent with the observed oxidation of Mg and trapping of small MgO particles by the electrolyte.

The above results demonstrate that the Mg electrorefining process is efficient. It operates at high current efficiency, high Mg recovery and low energy consumption (Table II).

Product Compositions and Potential Markets

Product composition, (Tables III and IV) determines its suitability for the various potential markets. The project objective was to produce Mg that would be suitable as a replacement for primary Mg in at least some of the potential markets.

Alloying of Al is the largest market for primary Mg. For primary purity alloys, Mg is added to primary Al, which is typically > 99.7% Al and < 0.3% (Fe + Si). So for this market, in which Mg is diluted between 20 and 100 times with 99.7% Al, the Mg product purity is adequate. Li content of the Mg product will be diluted to ~0.002% in the Al alloy before the melt treatment. This level is typical of alkali (Na) contamination of the primary-Al metal coming from Hall cells.

Table II. Laboratory-demonstrated performance of RE12TM electrorefining process

Parameter	Achieved	Target
Cell voltage @ CD 0.9 A/cm ² (V)	1	< 4
Specific energy consumption @ 0.9 A/cm ² (kWh/kg of Mg)	2.5 ^a	< 10
CO ₂ emissions associated with cell internal energy consumption (kg/kg Mg)	1	< 4
Electrorefining current efficiency (%)	~100	> 90
Mg recovery in the cathode product alloy (%)		
H ₂ evolution	96	> 90
Recovered Mg weight	87–100	
Al foundry alloy (wt.%)		
Mg	0.14	0.10
Li	0.05 ^a	
Al sheet alloy content (wt.%)		
Mg	0.75–1.1	0.75–1.1
Mg product purity (wt.%)		
Mg + Al	99.7%	> 99.7%
Li	0.22% ^b	
Total others	0.04%	< 0.3%
CO ₂ emission equivalent @ 2.5 kWh/kg of Mg (kg CO ₂ /kg Mg)	< 4	< 1
Production cost (\$/kg) (same for Al and Mg products)	< \$2	\$1.6–1.7

^aNot including energy required to melt scrap. ^bLi is going to be brought to specification level in product Al alloys during subsequent melt treatment

Table III. Cathode Mg product elemental composition (wt %). Cathode product used for ICP was recovered from the cathode surface during cell post-mortem

wt%	Sample		Comments
	#1	#2	
Mg	98.60	99.66	High selectivity for Mg
Al	0.86	0.0630	Variable between Mg droplets: different current density different Mg% in Al
Li	0.5400	0.2200	
Na	0.0055	0.0075	(Si + Fe) 0.02~0.04% << 0.3% target (Si+Fe+Cu+Zn+Mn+Co) 0.025~0.046%
Mn	<0.0010	0.0011	
Fe	0.0106	0.0021	NO electrolytic transfer to cathode PRIME PURITY product
Zn	0.0015	0.0016	
Si	0.0077	0.0395	
Cu	<0.0010		
Co	0.0035	0.0015	

This primary metal is always melt-treated to remove Na, and this treatment will equally well remove the residual Li. Consequently, the Mg cathode product is quite suitable as an alloying addition to many major primary-grade Al alloys.

Common Mg alloys are typically ternary with 3–10% Al content. Mg, however, is much less tolerant of other impurities. Consequently, the Al content of <1% shown in Table III would be acceptable for use in batching of Mg alloys. However, common Mg alloys contain very little Li, so the >0.2% Li content of the Mg would require that Li be extracted before use of the cathode product in the Mg-alloy market. Fortunately, the Al alloying market is large enough to consume more than can possibly be produced by the RE12TM process.

The anode Al product is the alloy batched at the Al remelt or secondary smelter plant. The laboratory runs have demonstrated that electrorefining at a current density of ~1 A/cm² can extract Mg from the Al melt down to a concentration of <0.14 wt.% Mg shown in Table IV.

This demonstration is adequate for producing major sheet and extrusion alloys, which typically contain 0.6–1.2% Mg. It is also adequate for many of the foundry Al-Si compositions. Only a slight improvement is required to satisfy the 0.1% Mg specification of the most stringent foundry products. This can be done by either an increase in the current density above 1 A/cm² or an increase in Mg mass transport in the Al pool through stirring. In a commercial concept, Al alloy flows through the cell continually and thus naturally provides stirring beneficial to Mg transport to the anode surface.

Table IV. Al product elemental composition (ICP wt.%)

wt%	Start	End	Comment
Al	95.56	98.80	Al concentrating as Mg moved to cathode
Mg	3.35	0.14	20X reduction, 95% Mg removed
Mn	0.5470	0.5430	No change, no undesirable electrolytic transfer to the cathode product
Fe	0.2220	0.2920	
Zn	0.1500	0.1530	
Si	0.0620	0.0550	
Cu	0.345		
Co	0.0070	0.0060	No change
Li	0.1020	0.0090	<< 0.05%, 10X reduction during electrorefining, 90% Li removed
Na	0.0019	0.0014	No change

DISCUSSION

The RE12TM electrorefining process fits well into the existing Al-scrap recycling, processing and recovery infrastructure. It technically replaces and is cost-competitive with the current procedure of Mg extraction through chlorination in an Al remelt/refining plant that does not recover Mg for recycling. RE12TM electrorefining produces recycled Mg product of a purity suitable for alloying prime Al that is batched from virgin Al and expensive hardener elements at a manufacturing cost equal to that of production of a secondary Al-alloy melt. This is approximately half of the cost of production of Mg by conventional methods.

In North America, Al secondary plants chlorinate ~2 million tonnes of foundry alloys, converting 30,000 tonnes of Mg to Mg chloride in the dross. Al can and automotive sheet producers use expensive primary Al to dilute Mg in 1.5 million tonnes of secondary sheet alloys coming from both new and post-consumer scrap. RE12TM electrorefining technology eliminates the need for these practices and produces a Mg product suitable for addition to prime Al-Mg alloys. Full implementation of RE12TM technology in North America could produce enough Mg to make 3 million tonnes of primary-quality Al-1% Mg alloys. Magnesium production by electrorefining is 5–10 times more energy efficient than production of primary Mg by MgCl₂ electrolysis, or by silico-thermic reduction of dolomite. This leads to corresponding reductions in greenhouse gas emissions.

CONCLUSION

All technical results obtained in the RE12TM project indicate that the electrorefining process for extraction of Mg from Al melt is technically feasible. The techno-economic analysis¹⁵ indicates high potential profitability for applications in Al foundry alloys as well as beverage—can and automotive—sheet alloys. This combination of technical feasibility and potential market profitability completes a successful proof of concept.

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