Molecular Resonant Frequency Enhancement of Metal Oxide Refining

1. A system (100) for refining a metal oxide can include a target material (110) and at least one energy source (120) associated with the target material (110). The target material (110) can include a metal oxide to be reduced to a metallic element. The energy source (120) can be configured to apply an energy input (130) to the target material (110). The energy input (130) can include an oscillating component having a frequency that is resonant with a molecular resonant frequency of at least one component of the target material. Additionally, a method of refining a metal oxide can include applying an energy input to a target material that includes the metal oxide to reduce the metal oxide to a metallic element. The energy input can include an oscillating component having a frequency that is resonant with a molecular resonant frequency of at least one component of the target material.

FIG. 1
MOLECULAR RESONANT FREQUENCY ENHANCEMENT
OF METAL OXIDE REFINING

RELATED APPLICATION
This application claims the benefit of U.S. Provisional Patent Application No. 62/019,264, filed June 30, 2014, which is incorporated herein by reference.

FIELD OF THE INVENTION
The present invention related to the electrically or equivalently powered separation of molecular compounds into their respective elements and derivative compounds. The invention has application of refining ores with the objective of obtaining an elemental metal or element of value and can have specific application, without being thereby limited, to the refining of alumina (aluminum oxide or Al₂O₃) for the recovery of elemental aluminum among other metals.

BACKGROUND INFORMATION
The invention described herein is related to the refining of metals or other elements from corresponding oxides, chlorides, carbonates or other refinable compounds containing desired metals. For purposes of discussion, the refining of aluminum from aluminum oxide is used as an example.

Aluminum in one or more of its various salt forms is one of the most abundant elements in the earth's crust and refined aluminum is one of the most useful of metals. However, elemental aluminum is seldom found in a raw state and is typically found as a molecular compound such that the aluminum is covalently bonded with other elements. Aluminum oxide, Al₂O₃ is a common form often found and mined as "bauxite" which may include not only aluminum oxides but also iron oxides, titanium oxides, other minerals in lesser proportion, and clay. Refined aluminum is useful as a strong, lightweight and corrosion resistant metal, and is frequently commercially blended with other metals and compounds as a component of metallic alloys.

In its early discovery and isolation, measured in grams and ounces, aluminum was a rarity and a curiosity and seemed more valuable, at least rarer than gold. In a later time, by
invention, it became possible to refine aluminum in quantity and at relatively low cost. In the last few years, worldwide aluminum production has risen to more than 50 million metric tonnes (110 billion lbs.) per year. This number does not include the utility of recycled aluminum that moves from the waste piles back into useful application.

There is a strong affinity for aluminum to oxygen such that aluminum oxide is formed by nature or processes as the two associating elements release energy in an exothermic reaction. To then refine the aluminum oxide back into its constituent elements requires both a replacement of the heat or energy of formation and a quasi-mechanical process of separating the two elements lest they recombine in the instant of dissociation.

Refining of aluminum made a dramatic advancement with development of the Hall-Heroult process. In the 1880s, there was a near simultaneous invention on both sides of the Atlantic when Charles Martin Hall in the U.S. and Paul Heroult in France both came on the concept of dissolving alumina (aluminum oxide) in molten cryolite and then applying principles of applying electrical energy through electrolysis to separate elemental aluminum from the oxygen. The flow of electrons from anode to cathode allowed freed molten aluminum, heavier than the molten cryolite, to sink to the bottom of the refining chamber while the oxygen migrated to the top of the chamber to be drawn away to a point of discharge.

An important enhancement of a bare anode electrolytic refining process came to involve the use of elemental carbon as the engaging anode material. In the presence of the dissolved oxygen ion in the cryolite solution, and with the aluminum being taken away, the carbon expresses its affinity for the oxygen and gives up the heat of formation associated with the making of carbon dioxide. This in turn contributes to the efficacy of the Hall-Heroult process and reduces the net process energy input associated with the primary object, the production of elemental aluminum. To the extent that manufacture of carbon anodes, either by a pre-bake or Soderberg technology, is less expensive than the contributed energy offset by the carbon dioxide formation, the carbon anode technology has become the industry standard. A particular drawback of the carbon anode is that consequent production of carbon dioxide in significant volume has come to be considered a pollutant as a greenhouse gas.

While a bare anode concept rather than a carbon anode in electrolytic aluminum refining is old prior art, U.S. Patent No. 6551489 B2 renews the carbon anode/carbon dioxide discussion by presenting a method of retrofitting existing aluminum refining cells or pots into an inert anode production mode. The application of this patent to existing refinery infrastructure could
essentially eliminate the production of carbon dioxide in the electrolytic refining process, but it would incur the added operating cost of electricity which the "heat of formation" of carbon dioxide displaces. Application of the patent does not eliminate the generation of fluorine based gases derived from the cryolite and fluxes used to promote the performance of the refining cell. Theoretical reversal of the heat of formation of aluminum oxide into its constituent elements is recorded in the literature at

1669.8 kilo-joules/gm-mol, approx. 3.9 kilo-watt-hrs/lb Al.

The heat of formation of carbon dioxide is recorded at

393.5 kilo-joules/gm-mol, approx. 1.38, say 1.4 kilo-watt-hrs/lb Al.

The net minimum theoretical energy requirement to produce a unit of aluminum is then

1669.8 - 393.5 =

1276.3 kilo-joules/gm-mol, approx. 2.5 kilo-watt-hrs/lb.

Noting the industry average of 6 - 7 kWh/lb of aluminum produced, the current Hall-Heroult process efficiency can be seen as 2.5kwh/lb./6 kWh/lb. = 0.41, which is not more than 40 - 45% apparent efficiency. Therefore, opportunities for continued improvement of aluminum processing remain.

**SUMMARY OF THE INVENTION**

Current technology typically uses one or more energy sources applied to a compound to reverse the process of formation of that compound, which process is typically exothermic, i.e., heat is released in the process of forming the compound, and hence heat or energy must be expended in not less than equal or greater magnitude per material unit (which implies inefficiencies) to accomplish a process reversal. It has been discovered that the refining process of many compounds into their respective elements can be enhanced (improved in efficiency) by including all or part of the required energy in the form of an energy input that includes energy with a frequency, an oscillation, at or nearly at that of the molecular resonant frequency (including its harmonics) and/or the molecular resonant frequency of one or more of its constituent atomic elements (including their harmonics). Specifically, metal oxide refining may be enhanced by delivering power to the refining cell, which power includes an element of the total power having an oscillating characteristic equivalent with a frequency resonant with an inherent molecular resonant frequency of the metal oxide or another component present in the refining cell. In some cases, the frequency can be at the resonant frequency. However, in other
cases, the frequency can be within 20% of the resonant frequency, and in some cases within 5% of the resonant frequency.

This does not mean that the energy required for the refining may ever be reduced below that of the fundamental "Heat of Formation" of the compound, but it does mean that an aspect of the inefficiency of the refining may be improved by applying part, or all, of the energy input in a form having the character of a molecular and/or elemental frequency of the constituent atom(s) or molecular compound of atoms.

There has thus been outlined, rather broadly, the more important features of the invention so that the detailed description thereof that follows may be better understood, and so that the present contribution to the art may be better appreciated. Other features of the present invention will become clearer from the following detailed description of the invention, taken with the accompanying drawings and claims, or may be learned by the practice of the invention.

**BRIEF DESCRIPTION OF THE DRAWINGS**

FIG. 1 is a schematic illustrating a system for refining a metal oxide in accordance with one example of the present technology;

FIG. 2 is a schematic illustrating a system for refining a metal oxide in accordance with one example of the present technology;

FIG. 3 is a process schematic illustrating a system for refining a metal oxide in accordance with one example of the present technology;

FIG. 4 is a flow chart illustrating a process for refining a metal oxide to form a reduced metal in accordance with the present technology;

FIG. 5 is a schematic of a reaction chamber in accordance with one example of the present technology.

FIG. 6 is a schematic illustration of another optional reaction chamber in accordance with one example of the present technology.

FIG. 7 is a schematic illustration of a reaction chamber and feedstock supply units in accordance with one example of the present technology.

FIG. 8 is a schematic illustration of a series of high voltage sources and reaction chambers in accordance with another optional example of the present technology; and

FIG. 9A is a graph of oxygen release over time in accordance with one example.
FIG. 9B is a graph of magnetic field as a function of time contemporaneous with FIG.

9A.

FIG. 10 A is a graph of vessel pressure over time in accordance with example 1.
FIG. 10B is a graph of magnetic field over time in accordance with example 1.
FIG. 10C is a graph of radiation over time in accordance with example 1.
FIG. 10D is a graph of oxygen percent over time in accordance with example 1.
FIG. 10E is a graph of $C_0_2$ release over time in accordance with example 1.
FIG. 10F is a graph of applied temperature over time in accordance with example 1.
FIG. 10G is a graph of internal sample temperature over time in accordance with example 1.

FIG. 11A is a graph of magnetic field over time in accordance with Example 2.
FIG. 11B is a graph of applied temperature over time in accordance with Example 2.
FIG. 11C is a graph of vessel pressure over time in accordance with Example 2.
FIG. 11D is a graph of $C_0_2$ release over time in accordance with Example 2.
FIG. 11E is a graph of oxygen percent over time in accordance with Example 2.
FIG. 11F is a graph of radiation over time in accordance with Example 2.
FIG. 11G is a graph of internal sample temperature over time in accordance with Example 2.

FIG. 12A is a graph of oxygen percent over time in accordance with Example 3.
FIG. 12B is a graph of $C_0_2$ release over time in accordance with Example 3.
FIG. 12C is a graph of vessel pressure over time in accordance with Example 3.
FIG. 12D is a graph of applied temperature over time in accordance with Example 3.
FIG. 12E is a graph of internal sample temperature over time in accordance with Example 3.

FIG. 12F is a graph of magnetic field over time in accordance with Example 3.
FIG. 13A is a graph of oxygen percent over time in accordance with Example 4.
FIG. 13B is a graph of vessel pressure over time in accordance with Example 4.
FIG. 13C is a graph of magnetic field over time in accordance with Example 4.
FIG. 13D is a graph of $C_0_2$ release over time in accordance with Example 4.
FIG. 13E is a graph of applied temperature over time in accordance with Example 4.
FIG. 13F is a graph of internal sample temperature over time in accordance with Example 4.
FIG. 14A is a graph of oxygen percent over time in accordance with Example 5.
FIG. 14B is a graph of CO₂ release over time in accordance with Example 5.
FIG. 14C is a graph of temperature over time in accordance with Example 5.
FIG. 14D is a graph of magnetic field over time in accordance with Example 5.

These drawings are provided to illustrate various aspects of the invention and are not intended to be limiting of the scope in terms of dimensions, materials, configurations, arrangements or proportions unless otherwise limited by the claims.

DETAILED DESCRIPTION

While these exemplary embodiments are described in sufficient detail to enable those skilled in the art to practice the invention, it should be understood that other embodiments may be realized and that various changes to the invention may be made without departing from the spirit and scope of the present invention. Thus, the following more detailed description of the embodiments of the present invention is not intended to limit the scope of the invention, as claimed, but is presented for purposes of illustration only and not limitation to describe the features and characteristics of the present invention, to set forth the best mode of operation of the invention, and to sufficiently enable one skilled in the art to practice the invention. Accordingly, the scope of the present invention is to be defined solely by the appended claims.

Definitions

In describing and claiming the present invention, the following terminology will be used.

As used herein, the terms "about" and "approximately" are used to provide flexibility, such as to indicate, for example, that a given value in a numerical range endpoint may be "a little above" or "a little below" the endpoint. The degree of flexibility for a particular variable can be readily determined by one skilled in the art based on the context.

As used herein, "adjacent" refers to the proximity of two structures or elements. Particularly, elements that are identified as being "adjacent" may be either abutting or connected. Such elements may also be near or close to each other without necessarily contacting each other. The exact degree of proximity may in some cases depend on the specific context.

As used herein, the term "alternating current" refers to any electric current that repeatedly cycles between two or more magnitudes and/or directions of current flow. The alternating current can follow various repetitive patterns or waveforms, such as a sinusoidal pattern, a square wave,
saw tooth wave, and others. Alternating current can in some cases reverse direction with each cycle in the repetitive pattern. In other cases alternating current can flow in one direction, while the magnitude of the current alternates between two or more values. Furthermore, the alternating current can have a constant frequency, or the frequency can change such as when the frequency is modulated. An electric current that travels through a medium "from the first electrode(s) to a second electrode(s)" can refer to a flow of negative charge (electrons) from the first electrode to the second electrode, or to a flow of positive charge from the first electrode(s) to the second electrode(s) (in which electrons actually flow in the opposite direction, from the second electrode to the first electrode).

As used herein, concentrations, amounts, and other numerical data may be presented herein in a range format. It is to be understood that such range format is used merely for convenience and brevity and should be interpreted flexibly to include not only the numerical values explicitly recited as the limits of the range, but also to include all the individual numerical values or sub-ranges encompassed within that range as if each numerical value and sub-range is explicitly recited. For example, a numerical range of about 1 to about 4.5 should be interpreted to include not only the explicitly recited limits of 1 to about 4.5, but also to include individual numerals such as 2, 3, 4, and sub-ranges such as 1 to 3, 2 to 4, etc. The same principle applies to ranges reciting only one numerical value, such as "less than about 4.5," which should be interpreted to include all of the above-recited values and ranges. Further, such an interpretation should apply regardless of the breadth of the range or the characteristic being described.

As used herein, the term "direct current" refers to any electric current that flows in a one dimensional manner without alternation of its polarity or direction. Note that an alternating current may be superimposed on a direct current circuit as in an alternating current voltage source may be connected in series with a direct current voltage source. At any given moment in time, while the current is equal through the multiple voltage sources, the net total voltage is the sum of the concurrently active voltage sources. A direct current source may also be connected in parallel with an alternating current source. In this case, the voltage sources by definition are equivalent while the total current is the sum of the currents provided by the respective voltage/current sources.

As used herein, the terms "light," "illumination," and "electromagnetic radiation" can be used interchangeably and can refer to light or electromagnetic radiation in the ultraviolet, visible, near infrared and infrared spectra. The terms can further more broadly include electromagnetic
radiation such as radio waves, microwaves, x-rays, and gamma rays. Thus, the term "light" is not limited to electromagnetic radiation in the visible spectrum.

As used herein, the term "molecular resonance frequency" refers to a frequency at which atoms in a molecule resonate vibrationally. A periodic driving force operating at a resonant frequency of a molecule can cause the molecule to vibrate with a large amplitude, because the vibrational energy of the molecule is conserved while the periodic driving force continually supplies additional vibrational energy. A molecule can have a single resonance frequency, or multiple distinct resonance frequencies.

As used herein, a plurality of items, structural elements, compositional elements, and/or materials may be presented in a common list for convenience. However, these lists should be construed as though each member of the list is individually identified as a separate and unique member. Thus, no individual member of such list should be construed as a defacto equivalent of any other member of the same list solely based on their presentation in a common group without indications to the contrary.

It is noted that, as used in this specification and in the appended claims, the singular forms "a," "an," and "the" include plural referents unless the context clearly dictates otherwise. Thus, for example, reference to "a particle" includes one or more of such features, reference to "a product stream" includes reference to one or more of such elements, and reference to "applying" includes reference to one or more of such steps.

Any steps recited in any method or process claim may be executed in any order and are not limited to the order presented in the claims. Means-plus-function or step-plus function limitations will only be employed where for a specific claim limitation all of the following conditions are present in that limitation:

a) "means for" or "step for" is expressly recited; and

b) a corresponding function is expressly recited. The structure, material or acts that support the means-plus function are expressly recited in the description herein.

Accordingly, the scope of the invention should be determined solely by the appended claims and their legal equivalents, rather than by the descriptions and examples given herein.

As used herein, the term "substantially" refers to the complete or nearly complete extent or degree of an action, characteristic, property, state, structure, item, or result. The exact allowable degree of deviation from absolute completeness may in some cases depend on the specific context. However, the nearness of completion will generally be so as to have the same
overall result as if absolute and total completion were obtained. The use of "substantially" is equally applicable when used in a negative connotation to refer to the complete or near complete lack of an action, characteristic, property, state, structure, item, or result.

5 Metal Oxide Refining

Reference will now be made to the exemplary embodiments illustrated, and specific language will be used herein to describe the same. It will nevertheless be understood that no limitation of the scope of the technology is thereby intended. Additional features and advantages of the technology will be apparent from the detailed description which follows, taken in conjunction with the accompanying drawings, which together illustrate, by way of example, features of the technology.

With the general examples set forth in the Summary above, it is noted in the present disclosure that when describing the system, or the related devices or methods, individual or separate descriptions are considered applicable to one other, whether or not explicitly discussed in the context of a particular example or embodiment. For example, in discussing a device per se, other device, system, and/or method embodiments are also included in such discussions, and vice versa.

Furthermore, various modifications and combinations can be derived from the present disclosure and illustrations, and as such, the figures should not be considered limiting.

It is observed in many, if not most mechanical and chemical processes that there is a certain stability in the evolved state that must be initially, even continuously overcome to get a new process of motion, a reversal of prior process into action. There is an energy of "breaking things loose," or "breakaway energy" as illustrated by breaking a rusted threaded nut loose from its bolt threads that must be overcome before the nut will start to move more freely. Although it may not be possible to improve on reversing the theoretical "heat of formation" of various compounds that may be involved in a variety of refining processes, the breakaway energy requirement can be reduced by catalyzing or otherwise facilitating efficiencies that can improve the economic viability of recovery of metals from raw materials including metal compounds.

At the atomic level where there is discussion of an atom having a nucleus of protons and neutrons surrounded by a cloud of electrons in a variety of shells, the electrons moving in a seemingly random yet ordered form, it appears that electrons are in motion within and about the atom from energy level to energy level in some consistent pattern, with a specific frequency of
motion. Thus when an atom or combination of atoms (molecule or compound) is specifically energized, it can be identified by the frequency of the electron cloud emission(s), often exhibited in the range of visible light for molecules, through the ultraviolet and into the X-Ray range for elemental atoms. Thus it is possible to develop resonant high frequency energy sources including laser light sources based on the use of particular elements or compounds as part of the fundamental energy or laser light source.

When energy is added to a system that has a fundamental frequency of motion, if the additive energy frequency is in harmony with the fundamental frequency (or frequencies) of a system, there is a coherence or resonance of the additive energy and the basic energy of the system.

Generally, resonance is the tendency of a system to oscillate with greater amplitude at some frequencies than at others. Frequencies at which the response amplitude is a relative maximum are known as resonant frequencies, or resonance frequencies. At these frequencies, even small periodic driving forces can produce large amplitude oscillations, because the system stores vibrational energy.

Resonance can occur when a system is able to store and easily transfer energy between two or more different storage modes (such as kinetic energy and potential energy). However, there can be some losses from cycle to cycle, called damping. When damping is small, the resonant frequency is approximately equal to the natural frequency of the system, which is a frequency of unforced vibrations. Some systems have multiple, distinct, resonant frequencies.

Resonance phenomena occur with all types of vibrations or waves. For example, types of resonance include mechanical resonance, acoustic resonance, electromagnetic resonance, nuclear magnetic resonance (NMR), electron spin resonance (ESR) and resonance of quantum wave functions. Resonant systems can be used to generate vibrations of a specific frequency (e.g. musical instruments), or pick out specific frequencies from a complex vibration containing many frequencies (e.g. filters).

The overall energy required for refining compounds into constituent elements can be reduced by including an element of resonant energy in the overall reversing the energy of the heat of formation, all or in part, when refining the compounds into the constituent elements. The resonant energy has an aspect of frequency, the frequency being able to resonate with one or more of the inherent resonant frequencies of the compound molecule or individual atoms of the compound.
The concept of frequency also includes the concept of wavelength. For a given frequency or wave length excitation, a response may be induced by something acting at the actual fundamental frequency or at certain fractional part of the fundamental (i.e. \( \frac{1}{2} \) or \( \frac{1}{4} \ldots \)) or at a multiple of the fundamental (i.e. 2 or 4\ldots). These related frequencies are often referred to as harmonics and may be helpful to address and include in a given system. The concept of frequency being useful in this invention includes resonant frequencies of the elemental atoms and/or of the molecular compounds along with the harmonic frequencies of the resonant frequencies that contribute to reducing metal to the elemental state.

Energy having a frequency character may present in a form of sound, radio, microwave, infrared, visible light, ultraviolet light, (including laser light), X-Ray, Gamma Ray, magnetic field, electrical voltage/current, or plasma. Molecular resonant frequencies are in a range or \( 10^{15} - 10^{19} \) Hertz with corresponding wavelengths in a range of \( 10^{-7} - 10^{-11} \) meters. In some aspects of the present invention, the energy can include electrical currents and the frequency can be in the range of \( 10^6 - 10^{13} \) Giga Hertz. Other forms of energy input such as ultrasonic, microwave, induction, X-Ray, Gamma Ray, proton beam, etc. can also be used. Molecular resonant vibrational frequencies for several representative materials include 2.6 THz for \( \text{Al}_2\text{O}_3 \) and 8.2 THz for \( \text{TiO}_2 \).

Electrical currents are inseparably connected with electrical voltage, voltage being the motive force behind the movement of electrons, the current, through a medium. If the voltage has an oscillating or frequency characteristic, the consequent and related current will be similarly influenced. By definition, electrical current flow is from a point or region of high electrical potential toward a region of lower potential. The electromotive force (EMF) or voltage will typically have one of two characteristics: Alternating Current (AC) or Direct Current (DC). Voltage from different sources may be combined in parallel or series upon a common path. If in series, the voltages will be additive and the current will be the same, if in parallel, the voltage will be common and the current will be in proportion to the amount offered.

In dealing with the analysis of electrical circuits, Ohm's Law applies.

\[
\text{Voltage (EMF in volts, Symbol } "E"	ext{)} = \text{Current (in amperes, symbol } "I"	ext{)} \times \text{Resistance (in Ohms, symbol } "R")
\]

\[
E = I \times R
\]

Electrical power in watts is defined as:

\[
\text{Power} = \text{Voltage} \times \text{Current} \text{ or } P = E \times I
\]
Substituting from Ohm’s Law for voltage $E = I \times R$

$$\text{Power} = I^2 \times R$$

Thus the power dissipated between two points in an electrical circuit is proportional to the square of the amperage times the resistance between the two points. Note that the same amount of power can be dissipated in a cell with higher voltage drop and lower amperage, while current technology works principally with lower voltage and higher amperage.

In electrolytic refining of aluminum from aluminum oxide, while electricity is used as the primary source of energy, the net consumption of electrons is zero. It is electrical energy transformed locally into thermal energy that is used to bring the process to and maintain it at temperature and to provide the energy needed to reverse the heat of formation that was released in the initial formation of the compound. The positive and negative electrical charges given to the anode and the cathode serve to draw the dissolved ore ions away from each other in solution as they are given energy to dissociate or to change their association (oxygen moves from the aluminum to the carbon or to an O2 state), but the electrolysis neither adds nor subtracts electrons from the fundamental elements of the compound. This leads to the conclusion that for a given process, energy to drive the process might be taken from a single source as it is in the Hall-Heroult process, or it might be taken from more than one source as it would be if a combustion flame were used to heat the pot or cell, thus providing part of the energy for the process and thus reducing the overall energy input or energy cost factor required of the primary electrical input.

Alternatively, secondary power may be taken from a primary electrical direct circuit with a secondary input of a direct or alternating current working in the same cell, or with a secondary input of energy from an induction coil, radio frequency generator, laser device, X-ray device, or similar device.

Energy inputs are required over and above that of the specific reversal of the heat of formation during refining of a compound into its respective elements. These secondary energy demands are mostly parasitic and can be thought of as inefficiencies to be minimized as much as possible. In the Hall-Heroult process, such energy demands include bringing the cell or pot and all of its components up to a suitable operating temperature and then maintaining that temperature in a cooler surrounding environment. Thermal maintenance involves heat losses to ambient and can be minimized with insulation and a tight process enclosure. Energy is also used to bring the cryolite solvent up to a desired process temperature. Additional energy is needed to bring the ore and process additives up to the process temperature as they enter the cell and are
dissolved in the solvent. This aspect includes the heat required to bring the refined metal, the waste slag or crust and the waste gasses up to the operating temperature. When using cryolite, the operating temperature is typically from about 900 °C to 1100 °C, although process temperatures can be varied. For example, additives can be included to lower the melting point of the reaction medium (e.g. molten cryolite) and can include, for example, aluminum fluoride.

Regardless, this heat is needed for the refined metal to remain liquid into further processing, but it is over and above the fundamental required heat of formation and becomes part of the process energy heat requirement.

According to some embodiments of the presently disclosed technology, metals can be produced from metal oxides through the use of low voltage, high amperage, direct current passed through a solution consisting of a molten solvent (for example cryolite which is Na₃AlFe) in which a finely powdered metal oxide has been dissolved. Alternative molten solvents can include, but are not limited to, Ta₂O₅, K₂TaF₇ for tantalum, alkali halides, alkaline-earth halides, and the like.

Employing embodiments of the present technology, an oscillating form of energy is imposed on or the existing, low voltage, high current electrical flow is modified such that in the net process, all or part of an imposed refining energy oscillates at a frequency that is resonant with a molecular resonance frequency (including partials and/or harmonics) of the metal oxide, its constituent atoms, or other components present in the solution. Without being bound to a particular mechanism, it is believed that including an alternating current voltage or separate energy input having a specific frequency correlated to a metal oxide molecule can cause the atoms within the molecule to resonantly vibrate at a high amplitude, helping to break the molecular bonds between the atoms and helping the atoms of the molecule to dissociate. The frequency of the added energy aspect, the alternating current can be at or near one or more of the molecular resonance frequencies of the molecule or its constituent atoms, so that the alternating voltage/current continuously reinforces the vibrations of the molecule or constituent atoms.

The above description focuses on application of the present technology to improve the efficiency of existing metal oxide refining processes, such as the Hall-Heroult process. However, the present technology more generally extends to treating a target material containing any metal oxide to reduce the metal oxide to a metallic element using any energy source configured to apply an oscillating energy input having a frequency that is resonant with a molecular resonant frequency of at least one component of the target material. FIG. 1 is a schematic of a system 100
for refining a metal oxide. The system includes a target material 110 comprising a metal oxide to be reduced to a metallic element. The target material can typically be contained within a suitable enclosure. In some examples, the enclosure can be a high temperature crucible, refractory metal container, or the like. The system can also include at least one energy source 120 operatively associated with the target material. The energy source is configured to apply an energy input 130 to the target material. The energy input includes an oscillating component having a frequency that is resonant with a molecular resonant frequency of at least one component of the target material.

In various embodiments, the energy input can be any type of energy that has an oscillating characteristic. For example, electromagnetic radiation inherently has an oscillating characteristic in that electromagnetic radiation has a frequency and wavelength. Sonic energy also inherently has an oscillating characteristic, because sonic energy is transmitted by pressure waves having a certain frequency. Alternating current has an oscillating characteristic, by which the alternating current cycles from a positive to a negative voltage at a certain frequency. Direct current normally has no oscillating characteristic when the direct current is driven by a single, constant voltage. However, an electrical current consisting of a direct current and an alternating current in series or parallel can result in a current that is always driven by a net voltage in one direction, but which has an oscillating characteristic in that the voltage increases and decreases at a certain frequency without switching the polarity of the voltage.

Consistent with the above description, the at least one energy source supplying the oscillating energy input can be selected from a direct current source, an alternating current source, a radio wave source, a microwave source, an infrared light source, a visible light source, an ultraviolet light source, an X-ray source, a gamma ray source, a laser, a maser, an ultrasound source, or other electromagnetic source. In some embodiments, the at least one energy source can include an electrical energy source associated with at least one electrode configured to supply an electric current to the target material. The electrode can be an anode or cathode, and in some cases the energy source can further include a second electrode.

In additional embodiments, the at least one energy source can include a primary electrical energy source configured to supply a primary constant voltage and a secondary electrical energy source configured to impose an oscillating component upon the primary constant voltage by induction, connection in series with, or connection in parallel with the primary electrical energy source. FIG. 2 shows a schematic of such a system 200, in which the primary electrical energy...
source 220 supplies a constant voltage electrical energy input 230 to the target material 210, while the secondary electrical energy source 240 supplies an oscillating voltage input 250.

Energy sources can be high voltage transformation units such as transformers and generators. In a specific embodiment, the energy source can include a Tesla coil. Tesla coils are a type of electrical transformer that can produce a high voltage, low current, adjustable or fixed frequency alternating current. Tesla coils can be designed and built to provide any desired voltage and frequency. A Tesla coil can also include a supply transformer to provide a primary voltage, and two coils to convert the primary voltage into a higher secondary voltage. In some cases, a Tesla coil can include a spark gap to prevent high frequency oscillations from backing up into the supply transformer.

As mentioned above, the target material can generally include the metal oxide to be reduced to a metallic element. In some cases, the target material can be substantially pure metal oxide. In other cases, the target material can also include additional compounds such as solvents and catalysts. In some embodiments, the target material can be in a solid state, a liquid state, or a mixture of both solid and liquid states. Frequently, the target material can be initially heated to a molten state optionally within a suitable solvent.

In a specific embodiment, the target material can include a metal oxide dissolved in an electrolytic solvent. In some cases, this system can also include electrodes in contact with the electrolytic solvent, and an electrical energy source configured to apply a voltage across the electrodes. In one example, the metal oxide can be aluminum oxide and the electrolytic solvent can comprise cryolite.

As mentioned above, the oscillating energy input can have a frequency that is resonant with a molecular resonant frequency of at least one component of the target material. In some cases energy input can resonate with a resonant frequency of the metal oxide molecules. In other cases, the metal oxide can dissociate into ions when the metal oxide dissolves in an electrolytic solvent, and the energy input can resonate with a resonant frequency of one or more of the ions. In further examples, the energy input can resonate with a resonant frequency of the electrolytic solvent, or a catalyst if present.

The present technology also extends to methods of refining a metal oxide. In one embodiment, a method of refining a metal oxide can include supplying an energy input to a target material comprising a metal oxide such that the metal oxide reduced to a metallic element. The energy input can include an oscillating component having a frequency that is resonant with a
molecular resonant frequency of at least one component of the target material. Additionally, any embodiment of a system described herein can also be applied to a method or process for refining a metal oxide, and vice versa. Therefore, methods of refining metal oxides can include steps to perform any of the functions performed in the systems described herein.

In some embodiments, the present technology can be used to improve efficiency of existing processes for refining metal oxides. One embodiment of this invention may be found in its application to current aluminum oxide refining technology, a technology which employs the so called Hall-Heroult electrolytic process for separating the aluminum of the compound from the associated oxygen. The process uses a containment cell or pot to serve as containment and as an electrical cathode. A quantity of molten cryolite sits in the pot into which a charge of prepared alumina (aluminum oxide) is introduced. An electrical anode principally of elemental carbon sits on top of the melt. The carbon is sacrificial and associates with the oxygen to reduce the net energy required of the process. The molten solution is conductive with some resistance. A direct current (DC) electrical voltage potential is established between anode and cathode and current flows through the solution. As the current flows, energy is released into the resistive solution according to the formula:

\[ \text{Power released} = (\text{current})^2 \times (\text{resistance}) \]

The process is described chemically as follows:

\[ 2\text{Al}_2\text{O}_3 + 3\text{C} + \text{Energy} \rightarrow 4\text{Al} + 3\text{CO}_2 \]

The elemental aluminum settles in the pot while the gaseous carbon dioxide is drawn off the process. The molten cryolite serves only as a catalyst and is recharged either in continuous feed or batch mode. The carbon anode is gradually consumed and periodically replaced.

In applying the present invention to this process, an alternating current voltage is applied to the current flowing through the pot. The applied current has a determined frequency or frequencies which is/are coherent or resonant with a molecular resonant frequency or frequencies of the target material such as aluminum oxide, its aluminum and oxygen components, or another component of the solution in the pot. When a determined element of the desired resonant energy is in play, there is an observable and measureable reduction of the gross amount of energy required to refine a unit of aluminum oxide towards the desired end product of elemental aluminum.

In another embodiment, the present invention can be applied to an alumina refining process using an inert anode instead of a carbon anode as described in United States Patent No.
6,551,489 B2 which is incorporated herein by reference. One benefit is that of avoiding production of carbon dioxide during the process. The cost is that of having to electrically provide the additional energy to replace that offered by the heat of formation of the carbon dioxide.

In a further embodiment of this invention an application of the technology can involve a voltage/current source that imposes a voltage between an anode and a cathode with aluminum oxide between. The anode and cathode can have the character of adjacent plates, of coaxial cylinders, or of a horizontal chamber, a cell or pot. An electric arc is established between the anode and cathode, with the oxide in between, in which the electrical discharge serves to dissociate the aluminum from the oxygen. The dissociation is facilitated and enhanced by a molecular resonant frequency imposed on/by the voltage/current source. The arc can be established either by a direct or an alternating current generator. The frequency can have either an amplitude modulation for DC voltage or AC voltage, a frequency modulation for AC voltage, or a combination of frequency and amplitude modulation for an AC voltage. The process takes place at a temperature above that of the melting point of aluminum. The aluminum drains to a basin of collection. The released oxygen is engaged, optionally entrained in a background flow of an inert gas and exhausted from the process.

The anode and cathode can be formed from any electrically conductive material. Unlike the anode used in the Hall-Heroult process, which must be carbon-based, the electrodes of this embodiment are not particularly limited to any materials other than requiring electrical conductivity sufficient to pass current through the aluminum oxide. The oxygen atoms form oxygen gas which is then separated from the metal. Thus, the electrodes are not consumed during the process.

FIG. 3 shows a generalized schematic illustrating a system 300 for refining a metal oxide to form a reduced metal in accordance with the present technology. The system includes a voltage source 305 which produces an alternating current voltage, a first electrode 310 electrically associated with the high voltage source, a second electrode 315 separated from the first electrode, and a metal oxide 320 oriented between the first electrode and the second electrode. In the particular embodiment depicted, the voltage source is a high voltage coil such as a Tesla coil having a secondary coil electrically connected to the first electrode by a wire 325, although any suitable voltage source can be used. The first electrode in this embodiment is in the form of a hollow cylinder through which a particulate metal oxide powder can flow via gravity.
The second electrode is a rod extending along the interior of the first electrode cylinder, such that the metal oxide particles travel between the first electrode and second electrode in an annular space surrounding the second electrode. Thus, the first electrode and second electrode form a reaction chamber which contains the metal oxide while the metal oxide is converted to metal. Notably, other reaction chamber configurations can be used such as, but not limited to, parallel plates and the like. The second electrode can be connected to a ground 330. The metal oxide powder can be refined into metal as the metal oxide passes between the first electrode and second electrode. The refined metal can then be removed through a metal product stream 335. Also depicted in FIG. 3 is an optional preheater 340 that can be used to preheat the metal oxide powder before the metal oxide powder enters the reaction chamber. In some embodiments, the metal oxide powder can enter the preheater through an inlet 345 and be transported through the preheater by an auger, which both moves the metal oxide powder and agitates the metal oxide powder to increase heat transfer. The preheated metal oxide powder can then exit the preheater through an outlet 350 and enter the reaction chamber. The preheater can include resistive heating or can utilize heat recovered from other heat sources. For example, in one aspect, heat recovered from at least one of the reaction chamber and reduced metal can be recirculated to the preheater. In one example, the preheater can be an induction or resistive heater adapted to heat the powder to a temperature from about 800 °F to about 1800 °F, and in the case of aluminum oxide to about 1200 °F to 1300 °F.

FIG. 4 shows a flowchart of one example of a process 400 including the steps of applying an alternating current voltage to a metal oxide, wherein the voltage has a frequency approximately equal to a molecular resonance frequency of the metal oxide, wherein the voltage is sufficient to produce the reduced metal and oxygen gas from the metal oxide 410, and recovering the reduced metal 420. The process can be performed using a system for refining a metal oxide to form a reduced metal as described herein. Each aspect of both the process and the system described in the present description can be applied to either the process or the system. For example, if the present description states that the system can include a Tesla coil which produces the alternating current voltage, then the process is understood to include applying an alternating current voltage produced by a Tesla coil.

Although FIG. 3 depicts one embodiment of a system for refining a metal oxide to form a reduced metal in accordance with the present technology, many other system designs can also be used. For example, the system can be a continuous, batch, or semi-batch system. The system can
also include electrodes, voltage sources, preheaters, and other components as depicted in FIG. 3, or these components can have various other designs. For example, FIGs. 5-8 illustrate various embodiments of the system and components of the system. FIG. 5 shows an exemplary reaction chamber 500 comprising a cylindrically-shaped electrode 505 and a rod-shaped electrode 510 extending along a central axis of the cylindrically-shaped electrode. FIG. 6 shows another exemplary reaction chamber 600 comprising a cylindrically-shaped electrode 605 and a rod-shaped electrode 610 extending along the central axis of the cylindrically-shaped electrode. The cylindrically-shaped electrode can optionally include a lead 612 that can connect to a suitable voltage source. The reaction chamber 500 can further include a feed inlet 615 to allow introduction of target material and/or solvent into the chamber and a complimentary outlet 620 to allow removal of materials from the chamber. FIG. 7 illustrates an exemplary reaction system 700 including the reaction chamber 705 and voltage source 710. FIG. 8 illustrates a larger-scale system 800 for refining a metal oxide to form a reduced metal, including a series of tesla coils 805, reaction chambers 810, and feed bins 815.

The first and second electrodes can have either positive or negative polarity. The direction of electric current flow is not particularly important to this process of separating the metal and oxygen atoms. Therefore, the first and second electrodes can be either a cathode or anode. In some embodiments, the alternating current can oscillate between positive and negative voltages, so that the direction of electric current can rapidly change direction. In some aspects of the present technology, the first electrode and second electrode can form a reaction chamber that contains the metal oxide. For example, as shown in FIG. 3, the first electrode can be a hollow cylinder and the second electrode can be a rod extending along the interior of the cylinder. These electrodes form a reaction chamber in which the metal oxide is contained within the annular space between the electrodes. As used herein, "contained" refers to controlling the metal oxide by maintaining the metal oxide between the electrodes, at least for a period of time. For example, in a batch process the reaction chamber can contain the metal oxide without any metal oxide leaving the reaction chamber for the duration of the refining process. The metal oxide can be treated stationary or can be mixed during treatment. However, in a continuous process, the reaction chamber can include an inlet and outlet through which metal oxide or refined metal can flow, so that the metal oxide is contained inside the reaction chamber during a residence time in the chamber, but then is allowed to exit the reaction chamber through the outlet. In some cases, the entire reaction chamber can be formed of the first and second electrodes. In other cases, only
a portion of the reaction chamber is formed of the electrodes. For example, the electrodes can form portions of side walls, or a floor and ceiling of the reaction chamber.

In an additional aspect, the reaction chamber can be a tube through which the metal oxide flows by gravity. In one embodiment, the exterior shell of the tube can be a cylindrically-shaped electrode electrically associated with the high voltage source. The second electrode can be a rod-shaped electrode extending along the interior of the tube. The tube can be oriented non-horizontally so that a metal oxide powder can flow through the tube under the influence of gravity. As the metal oxide powder flows through the tube, the high voltage source can apply an alternating current voltage to induce resonance in the metal oxide and split the metal oxide into metal and oxygen. In some cases, the application of the voltage can heat the metal to the point that the metal melts and exits the reaction chamber as a molten metal stream.

In some embodiments, the system can include a non-electrolytic non-oxidizing fluid in contact with the metal oxide, the first electrode, and the second electrode. Without being bound to a specific mechanism, it is believed that the non-electrolytic non-oxidizing fluid serves at least two purposes. First, the fluid can be ionized by a high voltage source to form plasma arcs between the electrodes. This allows current to pass through the metal oxide. Second, the fluid can displace oxygen gas given off as oxygen atoms are separated from the metal oxide, thereby protecting the refined metal from oxidation by oxygen radicals. The non-electrolytic non-oxidizing fluid can be chemically inert in the conditions of the metal oxide refining system. In other words, the non-electrolytic non-oxidizing fluid does not react with the metal oxide, metal, or oxygen gas present in the system, even under high voltages and high temperatures. Exemplary non-electrolytic non-oxidizing fluids that can be used include nitrogen, argon, xenon, krypton, or any other noble gas and mixtures thereof. In one specific embodiment, the non-electrolytic non-oxidizing fluid can be methanol. In some embodiments, the system can include a reaction chamber containing the metal oxide, with the entire remaining volume of the chamber filled by the non-electrolytic non-oxidizing fluid. In such embodiments, the metal oxide is not exposed to air or other materials besides the non-electrolytic non-oxidizing fluid and produced oxygen and reduced metal. Additionally, the non-electrolytic non-oxidizing fluid can be present at atmospheric or less than atmospheric pressure. For example, the pressure can be from about 0.1 bar to about 1 bar. However, any suitable pressure can be used and as a general guideline may range from about 0.1 bar to about 5 bar.
In one aspect of the present technology, the voltage can be sufficient to produce an electric arc that passes through the metal oxide. The high voltage source can impart a large electric charge to the first electrode, until the fluid between the first and second electrodes begins to ionize. The ionized fluid forms a plasma arc, allowing electric current to travel from the first electrode to the second electrode. The electric current can pass through the metal oxide between the electrodes, imparting energy to the metal oxide molecules. In embodiments where the metal oxide is in powder form, a single electric arc can travel through several metal oxide particles as the arc travels from one electrode to the other.

In many embodiments, low voltages can be used. As a general guideline, when using low voltage, a low voltage source can supply voltages from about 0V to about 600V, and in some cases up to about 100 V.

In some embodiments, high voltages can be used. The voltages can be, for example, much higher than the 3-5 V commonly used in the Hall-Heroult process. A high voltage source can supply voltages from about 1,000 V to about 2,000,000 V. For example, in one aspect the alternating current voltage can be ± 900 V to 3,000,000 V, and in some cases 1,000,000 V to 1,500,000 V. While these voltages are high, the corresponding amount electric current used can be much lower than in the Hall-Heroult process. In one aspect, the high voltage source can be configured to flow a current from the first electrode to the second electrode at an amperage of 0.2 A to 100A. In some embodiments, the high voltage source can supply a voltage from about 500,000 V to about 1,500,000 V and a current from about 20 mA to about 0.5 A. In one specific embodiment, the high voltage source can supply a voltage of about 500,000 V and a current of about 20 mA. In another specific embodiment, the high voltage source can supply a voltage of about 1,500,000 V and a current of about 30 mA. In yet another embodiment, the voltage can be about 1,500,000 V and the current can be about 0.5 A.

The alternating current voltage can have a frequency approximately equal to a molecular resonance frequency of the metal oxide. As used herein, "approximately" is used to provide flexibility. The degree of flexibility for a particular variable can be readily determined by one skilled in the art based on the context. In the specific context of the molecular resonance frequency, the closer the alternating current voltage can be to the actual molecular resonance frequency, the more efficiently the metal oxide can be refined into metal and oxygen gas. However, frequencies slightly higher or lower than the exact resonance frequency can still provide sufficient results. As used in the present description, the term "approximately equal to a
molecular resonance frequency of the metal oxide" can encompass the actual resonance frequency and other frequencies within 10% above and below the actual resonance frequency. However, in some embodiments the frequency of the alternating current can be within about 1% of the actual molecular resonance frequency. For metal oxides with multiple distinct resonance frequencies, these ranges apply to each resonance frequency.

The molecular resonance frequencies of a particular compound or metal oxide can be determined experimentally or calculated using mathematical molecular models. Factors that affect the molecular resonance frequency include the atomic masses of the atoms in the metal oxide molecule, the sizes of the atoms, bond lengths between the metal and oxygen atoms, ratio of metal atoms to oxygen atoms. One method of determining the molecular resonance frequency experimentally can include a high voltage source configured to produce an alternating current and a frequency modulation unit operatively connected to the high voltage source and adapted to control the frequency of the alternating current. The frequency modulation unit can be used to tune the frequency of the alternating current to find the optimal frequency for refining the metal oxide. For example, multiple test runs can be performed using different frequencies and then the best conversion rate of metal oxide to metal can indicate which frequency was closest to the actual resonance frequency.

In some embodiments of the present technology, the system for refining a metal oxide to form a reduced metal can include a frequency modulation unit operatively connected to the voltage source and adapted to control the frequency of the principal process voltage. The frequency modulation unit can be used to tune the frequency of the current, to find the optimal frequency for efficiently converting metal oxide to metal. The frequency modulation unit can also be used to switch between different resonant frequencies so that the system can be used to refine multiple types of metal oxides with different resonant frequencies.

In other embodiments, the high voltage source can be designed and built to produce only a single frequency which is known to be a resonant frequency (or desired harmonic) of the metal oxide desired to be refined, making the frequency modulation unit unnecessary.

In some embodiments, the system can include additional components adapted to transfer energy to the metal oxide to assist in splitting the metal oxide into elemental metal and oxygen atoms. In one aspect, the system can include a laser beam oriented to irradiate the metal oxide with laser light having a frequency approximately equal to the molecular resonance frequency of the object metal oxide. The light can excite the metal oxide at the molecular resonance
frequency. This effect, combined with the primary voltage/current applied to the process can more efficiently refine the metal oxide to metal.

In one specific embodiment, the metal oxide can be a metal oxide powder that is fed into an annular space between a cylindrically-shaped first electrode and rod-shaped second electrode. The voltage source can be electrically associated with the first electrode to apply an alternating current voltage to the metal oxide. A laser can be oriented to shine a beam along the length of the cylindrical electrode interior, irradiating the metal oxide powder. The laser and the voltage source can both operate at approximately a resonance frequency of the metal oxide. Thus the voltage source and the laser can both contribute to making the metal oxide molecules resonate and split apart into metal and oxygen atoms. In some embodiments, the voltage source can be a high voltage source such as a Tesla coil.

In another embodiment of the present technology, the system for refining a metal oxide to form a reduced metal can include a preheater configured to heat the metal oxide to a preheat temperature before the voltage is applied. Preheating the metal oxide can increase the efficiency of conversion of the metal oxide to metal. In one aspect, the preheater can include an electric heater. In another aspect, the preheater can include a heat exchanger supplied with a heat transfer fluid. The heat transfer fluid is not particularly limited and can include water, steam, combustion gases, hydrocarbon fluids, inert gases, hot product or byproduct streams from the system for refining metal oxide, and so on. In some cases, the product stream can be passed through the heat exchanger, or a heat exchange unit including multiple heat exchangers and a separate heat exchange fluid can be used to transfer heat from the product stream to the preheater. In one embodiment, the preheater can include a counter-current heat exchanger that transfers waste heat from the metal oxide refining process to the metal oxide feed. In other embodiments, multiple preheaters can be used in series to preheat the metal oxide to successively higher temperature. In some such embodiments, multiple units including a preheater followed by a pair of electrodes and a voltage source can be used in series to obtain a high purity of refined metal. The preheat temperature can generally be 176 °C to 1648°C, depending on the target materials and designed load. In some cases, the preheat temperature can be at least 648°C.

In some embodiments, the metal oxide can be in the form of a powder. Powders with an average particle size of 500 nm can be used. Powders with a particle size from 1μm can be particularly useful. As a general guideline, average particle sizes can often range from about 100 nm to about 1 mm, in some cases from about 200 nm to about 50 μm, in many cases up to about
5 µη. In one specific example, the metal oxide can be an Al₂O₃ powder with an average particle size of 500 nm to 1 µm.

The metal oxide can be selected from the group consisting of aluminum oxide, titanium oxide, lead oxide, zinc oxide, gallium oxide, alkaline earth metal oxides, and combinations of these materials. Each different metal oxide can have its own molecular resonance frequencies and its own requirements for preheat temperature, voltage, electric current, and so on. In one particular embodiment, the metal oxide is Al₂O₃.

Systems according to the present technology can be designed to produce a metal of any desired purity, up to 99% purity or better. In some cases, the metal product can be at least 95% pure. In other cases, the metal product can be at least 98% pure. In certain cases, the metal product can be at least 99% pure. In some cases, purity can be enhanced by using an appropriate molecular resonance frequency for the high voltage source and lasers, if used; longer residence time of the metal oxide between the electrodes; appropriate preheating temperatures; appropriate metal oxide particle sizes; and so on. In some embodiments, purity can be enhanced by passing the metal oxide through the system multiple times or passing the metal oxide through multiple pairs of electrodes in series to split more of the metal oxide molecules into metal and oxygen.

In some aspects of the present invention, a primary flow of refining energy is imposed on the process in a conventional means with a secondary input of energy imposed by a related or independent flow of energy. In one example, this can involve a secondary source of electrical power in series with, or in parallel with, or independent of a primary power source, the secondary source having an alternating current characteristic, the alternation being at or near one of the molecular resonant frequencies or harmonics of the compound being refined or another compound present with the compound being refined. In another example, a secondary source of energy can include laser light or induced heating effect (induction heating) or microwave heating or X-ray or gamma ray, the secondary source of energy having an alternating wave or frequency characteristic, the alternation being at or near one or more of the molecular resonant frequencies or harmonics of the compound being refined or another compound present with the compound being refined.

In the above, there has been focus on the enhancement of refining of aluminum oxide into elemental aluminum with the assist or aspect of a resonant frequency aspect of the voltage. In other embodiments, the processes and systems of this invention can be used to refine or assist in the refining of oxides or salts of other metallic elements such as lithium, beryllium, sodium,
magnesium, potassium, group II metals including titanium, lead, zinc, and gallium. For example, titanium is frequently recovered from raw minerals such as rutile, ilmenite, perovskite, and titante. In the case of titanium, the resonant frequency energy can be applied contemporaneously with processing using the well known Hunter, Kroll and FFC Cambridge processes. As these metals have various different conventional methods for refining, the processes of the present technology can provide different advantages and cost savings for each of these metals.

The foregoing detailed description describes the invention with reference to specific exemplary embodiments. However, it will be appreciated that various modifications and changes can be made without departing from the scope of the present invention as set forth in the appended claims. The detailed description and accompanying drawings are to be regarded as merely illustrative, rather than as restrictive, and all such modifications or changes, if any, are intended to fall within the scope of the present invention as described and set forth herein.

The described features, structures, or characteristics may be combined in any suitable manner in one or more examples. In the preceding description numerous specific details were provided, such as examples of various configurations to provide a thorough understanding of examples of the described technology. One skilled in the relevant art will recognize, however, that the technology may be practiced without one or more of the specific details, or with other methods, components, devices, etc. In other instances, well known structures or operations are not shown or described in detail to avoid obscuring aspects of the technology.

**EXAMPLE 1**

An amount of 200 gram of $\text{Al}_2\text{O}_3$ was heated in an enclosed vessel. Resonant frequency (2.6 THz) was applied using a high voltage source. FIG. 9A is a graph of release of oxygen from the alumina sample during application of magnetic field as recorded in FIG. 9B. These graphs collectively illustrate the relation of magnetic field generated by the input of the resonate frequency field on the release of oxygen from the alumina sample.

Data was collected during heating and application of the resonant frequency. FIG. 10 A is a graph of vessel pressure over time. FIG. 10B is a graph of magnetic field over time. FIG. 10C is a graph of radiation over time. FIG. 10D is a graph of oxygen percent over time. FIG. 10E is a graph of CO2 release over time. FIG. 10F is a graph of applied temperature over time. FIG. 10G is a graph of internal sample temperature over time.

**EXAMPLE 2**
An amount of 200 gram of AI2O 3 was heated in an enclosed vessel. Resonant frequency (2.6 THz) was applied using a high voltage source. Data was collected during heating and application of the resonant frequency. FIG. 11C is a graph of vessel pressure over time. FIG. 11A is a graph of magnetic field over time. FIG. 11F is a graph of radiation over time. FIG. 11E is a graph of oxygen percent over time. FIG. 11D is a graph of CO2 release over time. FIG. 11B is a graph of applied temperature over time. FIG. 11G is a graph of internal sample temperature over time.

EXAMPLE 3

An amount of 200 gram of AI2O3 was heated in an enclosed vessel. Resonant frequency (2.6 THz) was applied using a high voltage source. Data was collected during heating and application of the resonant frequency. FIG. 12C is a graph of vessel pressure over time. FIG. 12F is a graph of magnetic field over time. FIG. 12A is a graph of oxygen percent over time. FIG. 12B is a graph of CO2 release over time. FIG. 12D is a graph of applied temperature over time. FIG. 12E is a graph of internal sample temperature over time.

EXAMPLE 4

An amount of 200 gram of AI2O 3 was heated in an enclosed vessel. Resonant frequency (2.6 THz) was applied using a high voltage source. Data was collected during heating and application of the resonant frequency. FIG. 13B is a graph of vessel pressure over time. FIG. 13C is a graph of magnetic field over time. FIG. 13A is a graph of oxygen percent over time. FIG. 13D is a graph of CO2 release over time. FIG. 13E is a graph of applied temperature over time. FIG. 13F is a graph of internal sample temperature over time.

EXAMPLE 5

An amount of 200 gram of AI2O 3 was heated in an enclosed vessel. Resonant frequency (2.6 THz) was applied using a high voltage source. Data was collected during heating and application of the resonant frequency. FIG. 14D is a graph of magnetic field over time. FIG. 14A is a graph of oxygen percent over time. FIG. 14B is a graph of CO2 release over time. FIG. 14C is a graph of temperature over time.
CLAIMS

1. A system for refining a metal oxide comprising:
   a target material comprising a metal oxide or a metal salt to be reduced to a metallic
   element; and
   at least one energy source operatively associated with the target material and configured
to apply an energy input to the target material, wherein the energy input includes an oscillating
component having a frequency that is resonant with a molecular resonant frequency of at least
one component of the target material.

2. The system of claim 1, wherein the energy input is a form of energy selected from the group
consisting of electrical energy, electromagnetic energy, sonic energy, [any others?]

3. The system of claim 1, wherein the at least one energy source comprises an energy source
selected from the group consisting of a direct current source, an alternating current source, a
radio wave source, a microwave source, an infrared light source, a visible light source, an
ultraviolet light source, an X-ray source, a gamma ray source, a laser, a maser, an ultrasound
source, and combinations thereof.

4. The system of claim 1, wherein the at least one energy source comprises an electrical energy
source associated with at least one electrode configured to supply an electric current to the target
material.

5. The system of claim 1, wherein the at least one energy source comprises a primary electrical
energy source configured to supply a primary constant voltage and a secondary electrical energy
source configured to impose an oscillating component upon the primary constant voltage by
induction, connection in series with, or connection in parallel with the primary electrical energy
source.

6. The system of claim 1, wherein the at least one energy source comprises a high voltage coil.

7. The system of claim 1, wherein the target material is in a solid state, a liquid state, or a
mixture of solid and liquid states.
8. The system of claim 1, wherein the target material comprises the metal oxide dissolved in an electrolytic solvent.

9. The system of claim 8, further comprising electrodes in contact with the electrolytic solvent, wherein the energy source is an electrical energy source configured to apply a voltage across the electrodes.

10. The system of claim 9, wherein the metal oxide is aluminum oxide and the electrolytic solvent comprises cryolite.

11. The system of claim 1, wherein the at least one component of the target material is selected from the group consisting of the metal oxide, ions of the metal oxide dissolved in an electrolytic solvent, an electrolytic solvent, a catalyst, and combinations thereof.

12. A method of refining a metal oxide comprising supplying an energy input to a target material comprising a metal oxide such that the metal oxide is reduced to a metallic element, wherein the energy input includes an oscillating component having a frequency that is resonant with a molecular resonant frequency of at least one component of the target material.

13. The method of claim 12, wherein the energy input is a form of energy selected from the group consisting of electrical energy, electromagnetic energy, sonic energy, and combinations thereof.

14. The method of claim 12, wherein the energy input is supplied by an energy source selected from the group consisting of a direct current source, an alternating current source, a radio wave source, a microwave source, an infrared light source, a visible light source, an ultraviolet light source, an X-ray source, a gamma ray source, a laser, a maser, an ultrasound source, and combinations thereof.
15. The method of claim 12, wherein the energy input is supplied by an electrical energy source associated with at least one electrode configured to supply an electric current to the target material.

16. The method of claim 12, wherein the energy input is supplied by a primary electrical energy source configured to supply a primary constant voltage and a secondary electrical energy source configured to impose an oscillating component upon the primary constant voltage by induction, connection in series with, or connection in parallel with the primary electrical energy source.

17. The method of claim 12, wherein the energy input is supplied by an energy source comprising a tesla coil.

18. The method of claim 12, wherein the target material is in a solid state, a liquid state, or a mixture of solid and liquid states.

19. The method of claim 12, wherein the target material comprises the metal oxide dissolved in an electrolytic solvent.

20. The method of claim 19, wherein supplying the energy input comprises applying a voltage across electrodes in contact with the electrolytic solvent using an electrical energy source.

21. The method of claim 20, wherein the metal oxide is aluminum oxide and the electrolytic solvent comprises cryolite.

22. The method of claim 12, wherein the at least one component of the target material is selected from the group consisting of the metal oxide, ions of the metal oxide dissolved in an electrolytic solvent, an electrolytic solvent, a catalyst, and combinations thereof.
FIG. 3
Applying an alternating current voltage to a metal oxide, wherein the voltage has a frequency approximately equal to a molecular resonance frequency of the metal oxide, wherein the voltage is sufficient to produce the reduced metal and oxygen gas from the metal oxide.

Recovering the reduced metal

FIG. 4
### INTERNATIONAL SEARCH REPORT

**INTERNATIONAL APPLICATION**

**PCT/US 15/38648**

**A. CLASSIFICATION OF SUBJECT MATTER**

**IPC(8) -** C25C 1/00; C22B 9/00, 9/22 (2015.01)

**CPC -** C25C 1/00; C22B 9/22, 9/221

According to International Patent Classification (IPC) or to both national classification and IPC

**B. FIELDS SEARCHED**

Minimum documentation searched (classification system followed by classification symbols)

**IPC(8) -** C25C 1/00; C22B 9/00, 9/22 (2015.01)

**CPC -** C25C 1/00; C22B 9/00, 9/22, 9/221, 9/223, 9/225

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

PatSear (US, EP, WO, JP, DE, GB, CN, FR, KR, ES, AU, IN, CA, INPADOC Data); ProQuest: EBSCO; Google Scholar; refine, separate, metal, metallic element, reduce, AI203, alumina, bauxite, metal oxide, energy, electromagnetic, sonic, frequency, cryolite

**C. DOCUMENTS CONSIDERED TO BE RELEVANT**

<table>
<thead>
<tr>
<th>Category</th>
<th>Citation of document, with indication, where appropriate, of the relevant passages</th>
<th>Relevant to claim No.</th>
</tr>
</thead>
<tbody>
<tr>
<td>Y</td>
<td>US 2009/0324440 A1 (MARSH, J et al.) 31 December 2009; abstract; paragraphs [0001]-[0002], [0032], [0034], [0052], [0056], [0060], [0087], [0126], [0143], [0146], [0163]</td>
<td>1-22</td>
</tr>
<tr>
<td>Y</td>
<td>CN 103643259 A (ZHONGNING, S et al.) 19 March 2014; See Machine Translation; abstract; paragraphs [0020], [0027], [0050]</td>
<td>4, 8-10, 15, 19-21</td>
</tr>
<tr>
<td>A</td>
<td>US 7,628,340 B2 (CZIMMEK, PR) 08 December 2009; abstract</td>
<td>5, 16</td>
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<tr>
<td>Y</td>
<td>US 3,450,996 A (ABRAMYAN, EA et al.) 17 June 1969; abstract; column 1, lines 51-53</td>
<td>6, 17</td>
</tr>
</tbody>
</table>

Further documents are listed in the continuation of Box C. See patent family annex.

- Special categories of cited documents:
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**Date of the actual completion of the international search**

26 August 2015 (26.08.2015)

**Date of mailing of the international search report**

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**Name and mailing address of the ISA/Authorizing officer**

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