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INOVL, INC.

Lattice Energy Converter (LEC) Analysis and Optimization

ICCF-25 Supplemental Presentation

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Lattice Energy Converters (LECs) are potential 'green energy' devices for the direct conversion of thermal energy into electrical power without the use of naturally radioactive materials. Phenomenologically, a LEC is a current source, based on electrophysical dynamics of mobile ions in an electrolyte, rather than a voltage source based on electrochemical oxidation/reduction reactions. Conflicting dynamics of the ions in the electrolyte make the performance of LECs difficult to analyze and thus hard to optimize. In this presentation multiple simplifications of the mathematics of the motions of the ions will be made to explore which device parameters can be changed in order to provide greater power output. To get a voltage output a resistive load can be inserted into the current path of a LEC. The power delivered to the load comes from the ionization of the electrolyte between the electrodes of a LEC. If the electrolyte is a gas then hydrogen occluded hydrogen-host-material (hhm) such as electrodeposited palladium (Pd) or iron (Fe) between the electrodes will cause a LEC to spontaneously initiate the production of its current which sustains as long as the hhm remains occluded with hydrogen. One possible interpretation of this phenomenon is that a LEC derives its performance from Low Energy Nuclear Reactions (LENR) or 'cold fusion' but unlike 'hot fusion' there is no significant radiation or the production of radioactive waste.

From Volta to a LEC

Multiple Centuries of Progress

- In the late 18th-centuary, A Volta took two dissimilar metals, tin (Sn) and silver (Ag), and with "water" between them demonstrated an **electrophysical** (ion migration) source of weak electrical power
- Next, he replaced the Sn with Zn the Ag with Cu and the water electrolyte with "ley" [lye] and thus demonstrated a superior **electrochemical** (oxidation/reduction) source of strong electrical power known today as a single cell 'battery'
- In the early 21st- century, InovL researchers replaced the Zn with electrodeposited palladium (Pd) or iron (Fe), the Cu with brass, and the ley [lye] with either spontaneously ionized H_2 or D_2 gas and got
- An **electrophysical** LEC cell that generates 'green' electrical power

Multiple centuries have elapsed since A Volta's, *circa* 1799, original work with contact electrification, now known as contact potential difference (CPD) or Volta potential. Volta reported this work, in 1800, in a published letter written in French where he described an energy producing cell of tin (Sn), silver (Ag), and "water" as the electrolyte. However, his much more successful **electrochemical** (oxidation/reduction) than his **electrophysica**l (ion migration) energy cell. Cells of zinc (Zn), copper (Cu) and "ley" [lye] are remembered mostly today, since he combined these cells into a "column" or as it is sometimes called a "pile" to produce an early electric battery. In the mid 19th-centuary, T Graham, master of the royal mint, showed, in his 1868 *Proc Roy Soc* paper "On the occlusion of hydrogen by metals," that palladium (Pd) occludes large amounts of hydrogen gas. In the early 20th-century W Thomson (Lord Kelvin) verified experimentally the CPD effect. I Langmuir, who was awarded the Noble Prize in Chemistry in 1932, published (1916) an analysis of how a CPD cell continuously produces a current as long as the gas between the electrodes remains ionized. PE Ohmart (1966) received a US patent on a CPD cell that produces an electrical current when its gas is exposed to external ionizing radiation. Finally, in the early part of the 21st-centuary, InovL researchers have demonstrated, along with other international replicators, that CPD cells can spontaneously and continuously produce 'green,' CO_2 emission free, electrical power without the use of external ionizing radiation or materials that are normally considered to be radioactive. Is an occluded H_2 or D_2 gas LEC a demonstration of LENR? Note, author references are found in the Notes Pages.

Lattice Energy Converter (LEC) Description

- **Contact potential difference (CPD) is the critical parameter that both determines and characterizes LEC performance**
- **The presence and abundance of mobile ions in the electrolyte between the electrodes of a LEC's cell also is important**
- **When the electrolyte is an ionized gas than the source and nature of the spontaneous and self-sustaining ionizing radiation is important**
- **For hydrogen occluded electrodeposited hydrogen-host-materials, *e.g.*, iron (Fe) or palladium (Pd), gas ionization may be due to LENR**
- **There are multiple means of increasing the direct-conversion electrical power output of a LEC**

Lattice Energy Converters (LECs) are types of contact electrification devices based upon the contact potential difference (CPD) or Volta potential between dissimilar metal electrodes that have different work functions. Mobile ions, in the electrolyte in the gap between the electrodes, complete the circuit and electrical current will continue to flow as long as there are mobile ions between the electrodes. When normal temperature and pressure (NTP) gas as well as hydrogen occluded hydrogen-host-material (hhm), such as electrodeposited palladium (Pd) or iron (Fe), is between the electrodes, conduction will spontaneously initiate and self-sustain. The nature of both the source and the nature of the ionization radiation is currently unknown but no naturally radioactive materials are used in the construction of a LEC. One possible explanation being considered is that the ionization of the gas is due to Low Energy Nuclear Reactions (LENR) of 'cold fusion.' Currently, experimental LEC devices produce only micro-watts of power per square centimeter of active surface area of the hhm, but there are ways to increase the power output of a LEC. Some ways are: a) better metallurgy of the hhm; b) alternative gas mixtures; c) increased gas pressures; d) increased operating temperature; e) increased surface area of the hhm; f) and electrode separation distance; as well as changing from a gaseous electrolyte to a liquid, gel, or even a solid-state electrolyte.

LEC Characteristics Part I

- **A LEC is primarily an electrophysical device, based on the diffusion of mobile ions, that spontaneously and continuously generates electrical power without the use of naturally radioactive materials**
- **In its basic implementation it is comprised of two electrodes of different work functions, physically separated from each other, in contact with an intervening electrolyte and electrically connected so that a current will flow through the electrical connection whenever the electrolyte has mobile ions**
- **When the electrolyte is a gas it becomes spontaneously ionized when there is hydrogen occluded hydrogen-host-material (hhm), such as electrodeposited palladium (Pd) or iron (Fe), between the electrodes**

Ionization chambers (ICs)* are commonly used to measure the amount of radiation that irradiates the IC. For the purpose of analyzing the performance of LEC devices it is convenient to consider a LEC to be equivalent to a special type of IC, *i.e.*, a re-entrant or 4π IC where the ionizing radiation is internal to the IC and its measured voltage is the contact potential difference (CPD) under resistive load. Thus, the voltage of a LEC as an IC may be up to 3-orders of magnitude lower (0.1 V vs 100 V) than that of an IC used to detect radiation external to the IC. Therefore, the inclusion of ion diffusion and ion-ion recombination must be considered as critical parameters for LEC analysis. Rossi and Staub derive equations for the fractional loss of current density due to both diffusion and recombination.

$$(\partial i/i)_{diff} = 5 \times 10^{-2}/V = 5 \times 10^{-2}/0.5 \approx 1 \times 10^{-1}$$

$$(\partial i/i)_{recomb} = (2 \times 10^{-7}/V^2) d^2 n_0 = (2 \times 10^{-7}/V^2) 0.1^2 n_0 \approx 50$$

When evaluated for a LEC at $V = 0.5$ V, $n_0 = 6.24 \times 10^9$ ($i \approx 1$ nA), and separation $d = 0.1$ cm these results imply that the measured LEC current is at least 2 to 4-orders of magnitude too low due to incomplete capture of all of the ions in the gas

* BB Rossi, HH Staub, *Ionization Chambers and Counters, Experimental Techniques*, McGraw-Hill Book Co (1949) Chpt 2.

LEC Characteristics Part II

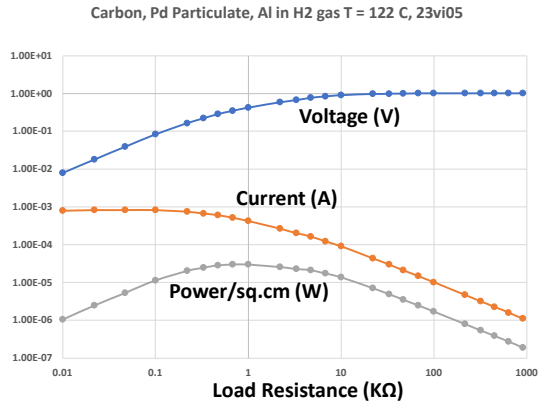
- **A LEC is a contact potential difference (CPD) device that uses an electrolyte containing mobile ions to complete the electrical circuit between two electrodes of different work functions**
- **A LEC using a liquid electrolyte, such as water, is thus similar to a voltaic cell of the type described by Volta in 1800**
- **When an electrolyte such as a liquid, gel, or solid-state material is used care must be taken avoid chemical reaction with the electrodes**
- **Thus, a LEC is an electrophysical (ion migration) rather than an electrochemical (oxidation/reduction) generator of electrical power**

Based on both experiment and published literature, a LEC is a contact potential difference (CPD) device that uses an electrolyte containing mobile ions to complete the electrical circuit between two electrodes of different work functions. When a LEC uses a liquid electrolyte, such as water, it is similar to a 'wet' voltaic cell of the type described by Volta in 1800 electrode materials must be chosen so that there is no electrochemical (oxidation/reduction) reactions between the electrolyte and the electrodes. This was not the case when Volta used cells of zinc (Zn) and copper. Even when a gel, or solid-state material is used care must be taken avoid chemical reaction with the electrodes. However, when care is taken to avoid chemical reactions between the electrolyte and the electrodes a LEC is an electrophysical (ion motion) rather than an electrochemical (oxidation/reduction) generator of electrical power without the use of naturally radioactive materials.

INOVL, INC. COMBINING INNOVATION AND NOVELTY TO PRODUCE NEW ENERGY SOLUTIONS

Experimentally Measured LEC Performance

- **Plane-parallel electrodes of aluminum (Al) and carbon (C) with electrodeposited palladium (Pd) particles on the carbon in hydrogen (H_2) gas**
- **Note that a LEC behaves as a current source (red) and should not be considered a voltage source at low cell voltages (blue)**
- **Power density per square centimeter into a resistive load (gray)**



Observe that at low values of increasing resistance the measured LEC cell voltages increase rapidly while the current is nearly constant as shown on a logarithmic scale. Thus, power delivered to the load increases as the voltage increases until some second phenomenon occurs to cause the current to decrease while the voltage remains nearly constant. Additionally, measurements of current-voltage (IV) characteristics of a LEC with injected current show that conduction is independent of the direction of flow through the LEC. This indicates that both positive and negative gaseous ions contribute to the current. Currently, the best model of a LEC is that it is a contact potential difference (CPD) device and that the electrolyte between the electrodes need to contain continuous and abundant mobile ions. This production of ions is achieved, in the case that the electrolyte is a gas, by some unknown process–possibly a low energy nuclear reaction (LENR). Although the spatial distribution of the ions within the gas is unknown, some insight into the optimization of the performance of a LEC will be achieved by reexamining the mathematics of the conduction of electricity through gases–a topic that has been studied for more than 125 years.

Limitations of Classical Conduction Analysis

- **Assumes that the ionization rate, *i.e.*, production of positive and negative ions per unit volume, $q_{\pm}$, is uniform throughout the gas, and that there are an equal number of positive and negative ions formed**
  - **This may not be true for a LEC since the source and nature of the ionization process is unknown**
- **Implicit in classical analysis is that the ionization rate, *q*, only depends on the intensity of the external source of radiation so that the measured current density, *i*, 'saturates, i_s' as the cell voltage increases**
  - **Experimentally, LEC internally generated current density, *i*, increases rather than saturating as the LEC cell voltage increases**

LEC conduction differs in two electrically important ways from that of externally ionized gas. Historically, most experiments were performed with uniform ionization of the gas and precautions were taken to prevent the external ionizing radiation from falling on the electrodes of the cell. At the present time there is no reason to believe that LEC gas is ionized uniformly and every reason to believe that the source and nature of the ionizing radiation originates internally in a LEC and possibly interacts with the electrodes of the cell.

Limitations of Experimental Technique

- **Electrolytes other than H_2 gas, D_2 gas, or air must be used with caution in the fabrication of a LEC**
  - **Volta, circa 1799, used a water-based electrolyte and zinc as one of the electrodes in his cell thus causing both electrophysical (ion migration) and electrochemical (oxidation/reduction) reaction to occur**
  - **The electrochemical reaction, $Zn + 2(OH)^- \rightarrow Zn(OH)_2 + 2e^-$, can take place when H_2O and zinc are used together to make a LEC, even if the water is only adsorbed, *e.g.*, Volta's 'dry piles,' thus dominating any electrophysical (CPD) current**
  - **When JB Kramer used air ionized by Monazite sand for the electrolyte in his "New Electronic Battery" the conduction he observed most probably was due more to adsorbed water on the sand than to ionization of the air by the radioactive thorium (Th) in the sand**

Another possible causes of experimental difficulty is that the cell's electrode separating insulator may become conductive or even become an electrolyte at elevated cell operating temperatures. Nylon becomes conductive at temperatures below 100 °C. 'High Temperature' epoxy becomes an electrolyte at temperatures greater than approximately 110 °C. Even ordinary ceramic tiles and glass microscope slides have been observed, at InovL's laboratory, to become electrolytes at temperatures greater than approximately 150 °C. Currently, the best insulator materials for use in LEC fabrication are silicone rubber and especially PTFE when a solid insulator can be used. Another possible cause of experimental difficulty is water vapor in gases used as an electrolyte. Carlin* performed experiments for the Army and published several reports on the conductivity of air as a function of relative humidity (RH) and concluded that ions composed of multiple water molecules were responsible for the conductivity of air. However, at the measured current densities of most experimental LECs, this contribution, if present, is at least 2- to 3-orders of magnitude too low to explain observed LEC conduction. Additionally, measurements on a Pd/D LEC near –55 °C showed no loss of LEC current, although any water vapor would have been frozen out of the cell's gas.

*_H.R. Carlon, Electrical Conductivity and Infrared Radiometry of Steam, Special Publication ARCSL-SP-80006, 1980

Confusion about CPD and Volta's Cells

- **There are two phenomena involved in Volta's cells–electrophysical (ion migration, CPD) and electrochemical (oxidation/reduction, O/R)**
  - **Volta didn't know he needed to separate these phenomena in 1800**
  - **Two types of 'piles'–'dry' (electrophysical) and 'wet' (electrochemical)**
    - **'dry' or CPD cells produce very little current but have a very long lifetime**
    - **"wet" or O/R cells produce abundant current but have a shorter lifetime**
    - **"wet' piles are what are generally referred to as voltaic piles or batteries**
- **Volta's 1800's cells "of copper or rather silver, applied each to a piece of tin, or zinc, *which is much better,* and as many strata of water, or any other liquid which may be a better conductor, such as salt water, ley [lye], &cc. or pieces of pasteboard, skin, &cc. well soaked in these liquids;" (italic emphasis added to English translation)**

Whether Volta's cells were electrophysical (due to the motion of ions without oxidation/reduction) or electrochemical (oxidation/reduction reactions) remained a subject of controversy for many years*. It is now known that both are true depending on the choice of electrode material and electrolyte. With his 'wet' cells using zinc (Zn), which Volta preferred, the reaction is electrochemical oxidation/reduction where the zinc gives up two electrons and hydrogen gas is evolved at the copper electrode. For his 'dry' cells without an obvious electrolyte, which produced less current, adsorbed water is the most probable explanation, *i.e.*, the process is electrophysical. LEC experiments conducted at InovL using finely ground 'decorative sand,' thorium dioxide powder, and Monazite sand all conducted a current when initially prepared but steadily decreased in performance as the temperature was raised to drive out adsorbed water. This indicates that Kramer's, "New Electronic Battery," Monazite sand results** were probably due to adsorbed water and this is why he did not formally publish his findings.

* H Chang, Dead or "undead"? The curious and untidy history of Volta's concept of "contact potential", *Science in Context*, 34(2) (2021) 221-247

** Anonymous, New Electronic Battery, *The Electrician*, (1924) 497

Optimization Analysis Goals

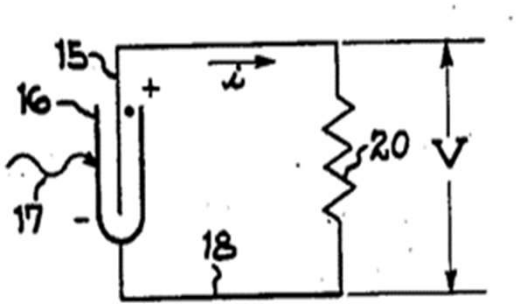
- **Determine the physical and chemical parameters that will give an increase of between 10^6 to 10^{10} in sustained LEC load power**
  - **Better metallurgy to increase the ionization rate *q***
  - **Electrode separation, *d*, that maximizes harvesting of the ions**
  - **Electrolytes that don't react chemically with the electrodes**
  - **Electrolytes for operation at temperatures greater than 100 °C**
- **Reexamine the mathematics on the conduction of electricity through gases in order to gain insight in how the interaction of the various gas parameters might help in the selection of an electrolyte and the physical implementation of a LEC**

Optimization of the power produced by a LEC is difficult since the origin and nature of the ionization of the gaseous electrolytes is unknown and possible chemical reactions between liquid, gel, and solid-state electrolytes has to be determined. Some general observations can be made. Two physical processes take place in the electrolyte of a LEC: a) generation of charge carriers (ions); and, b) recombination of charge carriers. Also, what ever the number of remaining charge carriers, they have to be harvested from the electrolyte in order to form the LEC's current output. Better metallurgy such a nano-tubes and nano-particles may provide 1- to 2-orders of magnitude more generated charge, *q*. The biggest gain, 3- to 5-orders of magnitude may come by controlling ion-ion recombination since it increases as the square of the ion-density, *n*, in gaseous electrolytes. For this reason, a revisiting of the mathematics of the conduction of electricity through gases is necessary. The mathematics of the conduction of electricity through gases is very difficult and even when simplifying assumptions are made since the electric field *E*, needed in a 2^{nd}-order nonlinear differential equations for the density of ions, *n*, is itself the solution of a 4^{th}-order nonlinear differential equation*.

* PA Tate, Effect of Diffusion on the Saturation Curve of a Plane Parallel Ion Chamber, *Phys Med Biol*, **13**(4), (1966) 521-532.

Ohmart's US 3,152,254 1964 Part I

- **Ionizable Gas (•)**
- **First dissimilar electrode (15)**
- **Second dissimilar Electrode (16)**
- **External radiation (17)**
- **External connecting lead (18)**
- **Load resistance (20)**

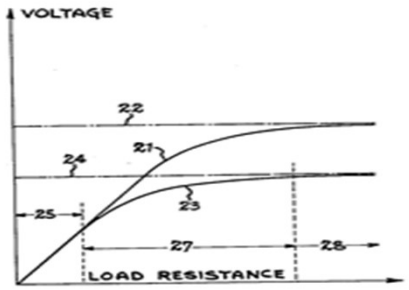


PE Ohmart, US 3,152,254, "Method and Apparatus for Converting Ionic Energy into Electrical Energy," and US 2,696,564, "Radio Electric Generator," "disclose and claim a cell for transforming radioactive energy directly into electrical current ⋯ ." In his publication* "A Method of Producing an Electric Current from Radioactivity" he states that "Experiments have shown that if a cell, made up of two electrochemically dissimilar materials separated by a gas is connected to a current measuring device, a small continuous current will be caused to flow from the more noble to the more active electrode without an external source of voltage when the separating gas is feebly ionized by exposure to nuclear radiation." Ohmart has in effect reduced I Langmuir's 1916 description of a CPD cell to practice. The InovL LEC, US 11,232,880 B2 differs from both of Ohmart's devices in that no normally radioactive material, or external source of ionizing energy, is required for the spontaneous and continuous production of electrical energy by a LEC.

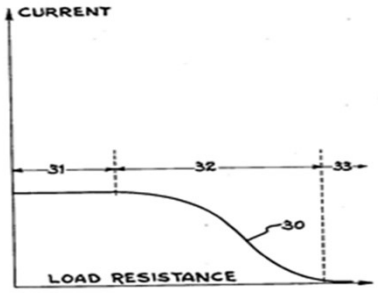
* PE Ohmart, A Method of Producing an Electric Current from Radioactivity, *J Applied Physics*, **22**(12), (1951) 1504-1505

Ohmart's US 3,152,254 1964 Part II

- **Voltage as a function of load resistance**



- **Current as a function of load resistance**



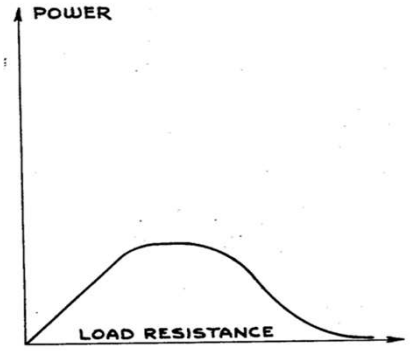
The first figure, voltage versus load resistance, shows that the voltage increases 'linearly' as the resistance increases in the same way that the voltage of a LEC increases 'linearly' with increasing load resistance. Since the voltage is being measured across a resistance the current being produced by the cell is simply the voltage divided by the resistance and is nearly 'constant' until the voltage increase is no longer linear. From the differential equations of both E Riecke* and KK Darrow** this departure from 'constant current' occurs when the electric field induced drift of the gaseous ions, $|\boldsymbol{v}_d| = |\mu \boldsymbol{E}|$ becomes equal to the diffusion of the ions due to the gradients in ion densities, $n_{\pm}$. At this point the *E*-field induced drift drives the positive ions, needed to complete the circuit of a CPD device, away from the high work function electrode and the load current starts to decrease. This is shown in the second figure, current versus load resistance. At low values of load resistance, where diffusion dominates the conduction and electric field ion drift is minimum, the current remains constant as the voltage increases. This behavior is characteristic of a current source.

* E Riecke, On approximately saturated currents between plane-parallel plates, *Ann d Physik*, **12** (1903) 820-827 in German

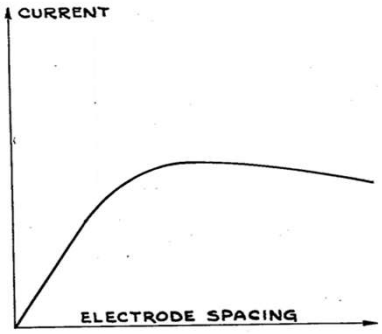
** KK Darrow, *Electrical Phenomena in Gases*, (1932) Chpt V.

Ohmart's US 3,152,254 1964 Part III

- **Power as a function of load resistance**



- **Current as a function of electrode separation**

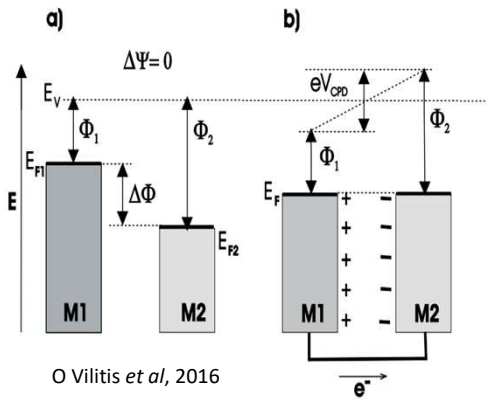


The first figure, power versus resistance, shows that Ohmart's measured voltage increases 'linearly' as the resistance increases in the same way that the voltage of a LEC increases 'linearly' with increasing load resistance. Since the voltage is being measured across a resistance the current being produced by the cell is simply the voltage divided by the resistance and is nearly 'constant' until the voltage increase is no longer linear. Power as a function of resistance is simply the product of the voltage by the current or, since the voltage is the only measured variable, load power is the square of the load voltage divided by the load resistance. When the *E*-field induced drift starts to drive the positive ions, needed to complete the circuit of a CPD device, away from the high work function electrode then the load current or voltage divided by load resistance starts to decrease while the voltage is more nearly constant. This produces the 'bell shaped' power versus resistance curve shown in the first figure. The second figure shows current as a function of electrode spacing having an optimum value. This is more difficult to explain since the conduction in the gas is a complicated function of many variables related by nonlinear differential equations. However, a simplified diffusion analysis by JJ Thomson* shows that the total amount of ionized gas between the electrodes is cubic in the electrode separation, however, ion-ion recombination and the diffusion time constant diminishes how much of this ionized gas becomes measurable current density.

* JJ Thomson, *Conduction of Electricity through Gases*, 1st Ed, 1903, Chpt 2

Contact Potential Difference (CPD)

- In 1800 Alexandro Volta reported that when two uncharged dissimilar metals were brought into contact and then separated each of the metals would acquire a different charge
- It is now known that this CPD or charge difference results from an equilibration of the Fermi levels of the two metals with different work functions (WFs), Φ
- $\Delta\Psi$:= CPD, Φ := WF



O Vilitis *et al*, 2016

In 1800 Volta* reported that when two dissimilar metals were brought into contact and then separated, they would become charged. Today this phenomena is called Volta Potential or Contact Potential Difference (CPD). There has been much confusion** about this phenomena since Volta's 'piles' or stacks of cells had different electrode material and used different electrolytes between the electrodes. However, CPD is a real electrophysical process*** distinct from the electrochemical (oxidation/reduction) that was the dominant source of current in Volta's zinc (Zn) versus copper (Cu) 'piles.' CPD results from the electrical connection of two material with different work function and a subsequent equilibration of the material's Fermi levels****.

* A Volta, On the electricity excited by the mere contact of conducting substances of different kinds. ⋯ , *Phil Trans Roy Soc London,* **90** (1800) 403-431, in French, **Sept** (1800) 289-311, English

** H Chang, Dead or "undead"? The curious and untidy history of Volta's concept of "contact potential", *Science in Context*, 34(2) (2021) 221-247

*** I Langmuir, The Relation Between Contact Potentials and Electrochemical Action, *Trans American Electrochemical Society*, **XXIX**(125), (1916) 173-217.

**** O Vilitis *et al*, Determination of Contact Potential Difference by the Kelvin Probe (Part I), *Latvian J Physics and Technical Science,* 2 (2016) 48-56.

From Cells to a Battery

- Volta's 'wet cells' used electrodes "of copper or rather silver, applied each to a piece of tin, **or zinc, which is much better**, and as many strata of water, or any other liquid which may be a better conductor, such as salt water, ley, &cc. or pieces of pasteboard, skin, &cc. well soaked in these liquids;" (emphasis added)
- Multiple cells can be stacked in a "*colonne*" or "column" to form a 'pile' or battery
- Whether the cells are electrochemical or electrophysical depends critically on the composition of the materials used
  - **Zinc (Zn) reacts with hydroxyl ions (OH^-) to form $Zn(OH)_{2\,(s)} + 2e^-$ –electrochemical (oxidation/reduction)**
  - **Neither silver (Ag) nor tin (Sn) normally reacts with pure water –electrophysical (movement of charged ions)**

Whether these cells were electrochemical (oxidation/reduction reactions) or electrophysical (due to the motion of ions without oxidation/reduction) remained a subject of controversy for many years*. It is now known that both are true depending on the choice of electrode material and electrolyte. With his 'wet cells' using zinc (Zn), which Volta preferred, the reaction is electrochemical oxidation/reduction where the zinc gives up two electrons and hydrogen gas is evolved at the copper electrode. For his 'dry cells' without an obvious electrolyte, which produced less current, adsorbed water is the most probable explanation, *i.e.*, the process is electrophysical. LEC experiments conducted at InovL using finely ground 'particulate material,' thorium dioxide powder, and Monazite sand all conducted a current when initially prepared but steadily decreased in performance as the temperature was raised to drive out adsorbed water. This indicates that Kramer's, "New Electronic Battery," Monazite sand results** were probably due to adsorbed water and this is why he did not formally publish his findings.

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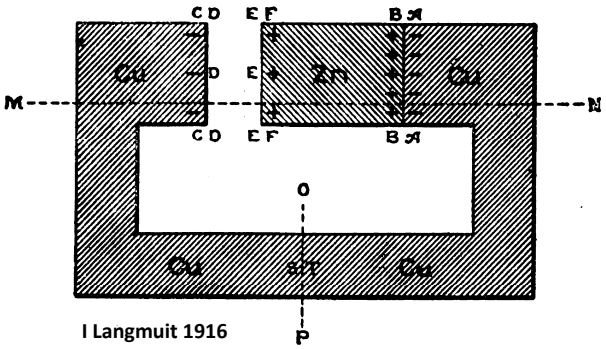
** Anonymous, New Electronic Battery, *The Electrician*, (1924) 497

Langmuir's 1916 Explanation of a CPD Cell

- "If we maintain the gas in an ionized condition, current will continue to flow. This current represents a definite amount of energy per second, equal to the product of the current by the contact potential."
- "It is thus clear that the energy of the current is supplied originally by the ionizing agent." – Approximately 36 eV per ion pair formed



I Langmuit 1916

In 1916 I Langmuir* writes with regard to contact potential difference (CPD) cells "The case is so simple when ionized gas is employed that a closer study of it will help to clarify our ideas as to the mechanism of such action.

If we maintain the gas in an ionized condition, current will continue to flow. This current represents a definite amount of energy per second, equal to the product of the current by the contact potential. Where does this energy come from? Where is the seat of the electromotive force which causes the current to flow?

It is evident that there is no permanent source of energy at the junction of the metals. But it takes energy to produce ionized gas, and this ionization is destroyed by the flow of the current. It is thus clear that the energy of the current is supplied originally by the ionizing agent."

* I Langmuir, The Relation Between Contact Potentials and Electrochemical Action, *Trans American Electrochemical Society*, **XXIX**(125), (1916) 173-217.

Interpreting Langmuir's CPD Cell Explanation

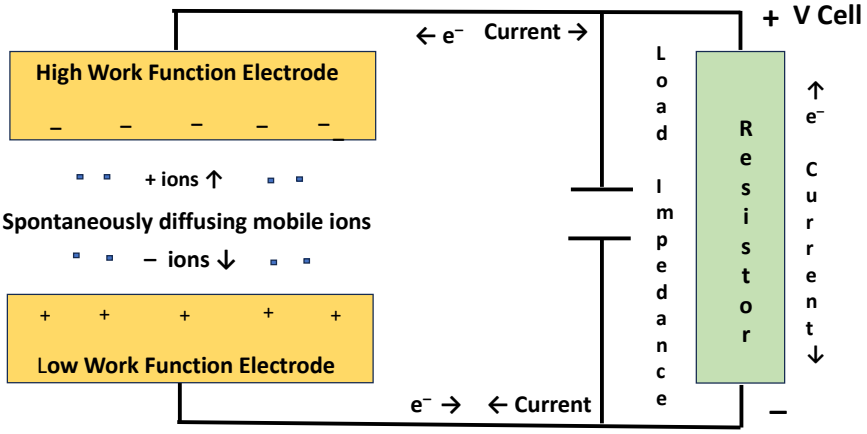
- Langmuir states: "Suppose we place an inert gas in the gap between *C* and *F* and ionize this gas by a radioactive substance or in any other manner. The positive ions will be drawn to *C* and the negative to *F*."
  - This discharges the negative charge at *C* and the positive charge at *F*
  - However, to maintain the current new negative charges must flow from *F* to *C* or conventional current must flow from *C* to *F* making *C* positive relative to *F*
  - **This is counter intuitive, since a positive potential repels positive charges**
- The counter flow of positive ions is resolved by noting that the gaseous ions move both by drifting in an electric field and by diffusing against it
  - **This explains why a LEC behaves as a current source at low electric fields**
  - **This explains why LEC voltage and current don't simultaneously go to zero**

I Langmuir * continues to writes "On the other hand, the force which causes the current to flow has nothing to do with the ionization, An electric field exists in the space between the electrodes *C* and *F* and therefore the ions move towards the electrodes. It is this field which must be looked upon as the immediate cause of the flow of current. This explains why the energy of the current is proportional to the contact-electromotive force and not to the ionizing potential of the gas.

A sharp distinction must be drawn between "difference of potential" and "electromotive force." We have already defined difference of poential as equal to dW/de, that is, as the work per unit charge when the charge becomes infinitesimal. We may now define electromotive force as W/e where W is the work done when an electron (charge e) moves from one place to another. Thus electromotive force is that which tends to cause current (actual electrons and ions) to flow."

* I Langmuir, The Relation Between Contact Potentials and Electrochemical Action, *Trans American Electrochemical Society*, **XXIX**(125), (1916) 173-217.

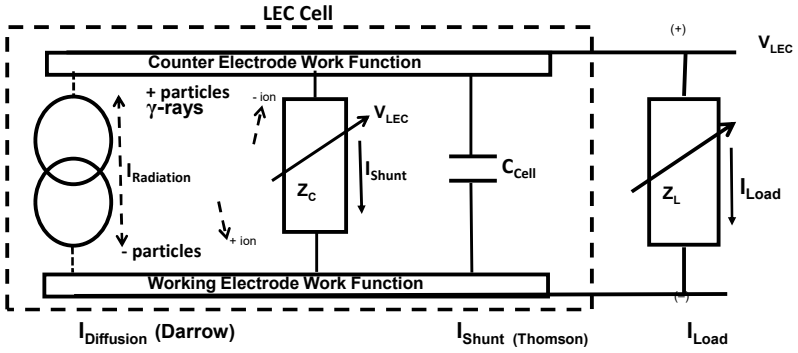
Electrical Circuit of a CPD LEC



The electrical transformation from I Langmuir's* analysis of the electrical properties of a CPD cell to an implemental CPD LEC is simple. The Cu–Cu junction, located at OP in his figure of a CPD cell, through which the cell current flows is opened and a resistor is inserted. The resistor still allows electrons (e^-) to flow from the low work function electrode to the high work function electrode, however, a voltage, V_{cell}, is now developed across the resistor. Since a LEC only needs spontaneously diffusing mobile ions between the electrodes, this opens up the possibility of the use of electrolytes other than a gas, *e.g.*, liquid, gel, or even solid-state electrolytes. However, care must be taken to insure that the electrodes do not react chemically with the electrode material. Additionally, when active hydrogen-host-material is dispersed in these non-gaseous electrolytes increased electrical power density has been measured from experimental LEC cells.

* I Langmuir, The Relation Between Contact Potentials and Electrochemical Action, *Trans American Electrochemical Society*, **XXIX**(125), (1916) 173-217.

Phenomenological Equivalent Circuit



$$S(\mu^- k_B T\, dn^-/dx - \mu^+ k_B T\, dn^+/dx) - S(n^+\mu^+ + n^-\mu^-)E = V_{LEC}/R_L$$

where current density is $i := I/S$, diffusivity is $D := \mu k_B T$, $V_{LEC} = \int E dx$,
and the total diffusive ion flux is $I/e = S(\mu^- k_B T\, dn^-/dx - \mu^+ k_B T\, dn^+/dx)$

Thus, I and E do not need to go to zero together!

In this phenomenological equivalent circuit, which can be used when designing additional circuitry to go with a LEC, the balancing diffusing ions against drifting ions has been replaced by a voltage dependent impedance, Z_C, which is in shunt with the load impedance, Z_L.

Conduction of Electricity Through Gases

- **The mathematics of the conduction of electricity through 'dense' gases, *i.e.*, low values of electric field, *E* [V/cm], to gas pressure, *p* [torr] (E/p < 2), has been studied for many years since JJ Thomson's pioneering 1899 publication of the equations with no diffusion term**
- **In 1903 E Riecke published, in German, a complete set of equations for the conduction of electricity including terms for the diffusion of the ions and showed that these equations, which have no known general analytic solution for the electric field, could be solved by successive approximation**
- **In 1932 KK Darrow derives the complete set of conduction equations by first considering the conservation of charge within the gas and then by a first integration of these equations to find the current density as a function of both diffusion and electric field induced ion drift**

The conduction of electricity through gases has a long history going back to the late 18-hundreds. JJ Thomson* published an abbreviated set of differential equations in 1899 that omitted terms for the diffusion of the ions. Even in this simplified form Thomson was not able to find a general analytic formula for the electric field distribution within the gas. In 1903,E Riecke** published, in German, a full set of differential equations and showed how to solve for the electric field by the method of successive approximation. KK Darrow***, in 1932, derived the differential equation for the conduction from the conservation of charge equations and a first integration of their difference. He showed that the current density was a function of both the electric field induced drift of the ions and the gradient of the ion densities. Since the voltage between the electrodes is the integral of the electric field, the current through the gas does not have to go to zero when the cell voltage is zero as there is still the diffusion of ion terms.

* JJ Thomson, On the Theory of the Conduction of Electricity through Gases by Charged Ions, *Phil Mag* S5 **47**(286), (1899) 253-268

** E Riecke, On approximately saturated currents between plane-parallel plates, *Ann d Physik*, **12** (1903) 820-827 in German

*** KK Darrow, *Electrical Phenomena in Gases*, (1932) Chpt V.

1-D Charge Conservation Equations

- Let the rate of generation of positive, q_+ [ion/cm^3·s], and negative, q_-, ions be equal and that the Coulomb dispersion of identically charged ions can be neglected, *i.e.*, $\alpha n_+ n_- < q_\pm$
- Generation Recombination Ion Diffusion Ion Drift

$$q_\pm - \alpha n_+ n_- + D_\pm d^2 n_\pm / dx^2 - \pm \mu_\pm d(E n_\pm)/dx = 0$$

- $n_\pm$ [/cm^3] are the number densities of the ions,
  α [cm^3/s] is the recombination coefficient of the ions,
  $\mu_\pm$ [cm^2/V·s] are the mobilities of the ions,
  E(x) [V/cm] is the electric field strength as a function of position, and
  $D_\pm = \mu_\pm (k_B/e)\, T$ [cm^2/s] are the diffusion coefficients of the ions with Boltzmann constant, k_B, electric charge, e, and temperature T

These conservation of charge differential equations are derived in KK Darrow's 1932 treatise*. They show the interrelationship between ion generation, $q_\pm$, and ion-ion recombination, $\alpha n_+ n_-$, as well as the interrelationship between ion diffusion and ion drift. One optimization choice, to increase the performance of a LEC, is to increase ion generation and minimize recombination while also increasing diffusion and minimizing ion drift. However, there is an interplay between recombination and diffusion since recombination is greatest midway between the electrodes and thus effects the gradients of the ion densities, $n_\pm$ which determine ion diffusion. Therefore, the electrode separation distance may become one of the most important design variables in the optimization of LEC performance.

* KK Darrow, *Electrical Phenomena in Gases*, (1932) Chpt V.

First Integral of Charge Conservation Equations

- Let *i* be current density then *i*/*e* is the number of charges per second

$$i/e = (n_+\mu_+ + n_-\mu_-)E(x) + D_-dn_-/dx - D_+dn_+/dx$$

- Darrow 1932: "I pause to point out that [this] equation may be derived ··· by subtracting one from the other [of the previous equations], and integrating once with respect to *x*
- This equation, including the diffusion terms, was first published by E Riecke in 1903 who suggested that it and the preceding equations could be solved for *E*(*x*) by successive approximation
- Note: there is no known analytic expression for *E*(*x*) and estimating *E*(*x*) requires solving a 4th-order non-linear differential equation

This first integral of the charge conservation differential equations including diffusion was first published, in German, by E Riecke* in 1903 and subsequently by KK Darrow* in 1932. Note that the cell voltage, *V*, between the electrodes is the integral of the electric field, *E*, and that the cell current, *I*, is the integral of the current density, *i*, over the surface area of the electrodes; then the 'conduction equation' can be expressed in terms of the measured LEC cell voltage, *V*, and load resistance, *R*, since $I = V/R$. The difficulty in using the conduction equation at high values of *R* as the cell voltage is approaching its 'open circuit' value of CPD is that there is no known analytic solution for the electric field, *E*. For plane-parallel electrodes, estimating *E, even* with the simplifying assumption that $D_+ = D_-$, requires the solution of a 4th-order nonlinear differential equation that does not have an analytic solution. It is recommended that a numerical solution of the equations be undertaken that is compatible with measured LEC cell current boundary conditions.

* E Riecke, [On approximately saturated currents between plane-parallel plates], *Ann d Physik*, **12** (1903) 820-827 in German

**KK Darrow, *Electrical Phenomena in Gases*, (1932) Chpt V.

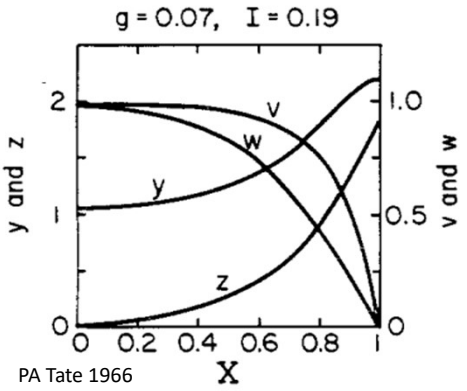
Historical Perspective on the Equations

- **For dense gases at low values of *E*/*p* [V/cm·torr] , such as *E*/*p* ≤ 2, the conduction of electricity through gas equations primarily have been used to analyze and characterize the performance of gaseous electronic devices such as ionization chambers**
- **For these devices the cell voltage is large (≈ 100 V), the electrode spacing is large (≈ 1 cm), and diffusion of the ions can be neglected as was shown by Rossi and Staub, *Ionization Chambers and Counters*, 1949, Chpt 2**
- **For InovL's experimental LECs, the cell voltage is small (< 1 V), the electrode spacing is small (< 0.1 cm), and diffusion of the ions predominates while the electric field is of secondary importance**

The mathematics of the conduction of electricity through the gas of a LEC is significantly different that that studied historically. For a LEC, cell voltage is low and diffusion and recombination of the ions dominates the performance of LEC devices. Historically, cell voltage is assumed to be high and diffusion of the ions is not a significant factor in the analysis of the conduction.

Conduction Including Diffusion, $I = j/j_s$

- $I := j/j_s$ normalized current density
- $g = 4D\tau/d^2$:= ion lifetime/diffusion time
- $v := n_+/(q/\alpha)^{1/2}$ normalized +ion density
- $w := n_-/(q/\alpha)^{1/2}$ normalized –ion density
- X := normalized abscissa
- y := normalized electric field
- $z = (j_+ - j_-)/(j_+ + j_-)$



PA Tate 1966

PA Tate* numerically solved the 4th-order nonlinear differential equation with assumptions and boundary conditions that are not representative of experimental LEC performance. It is recommended that the equations be resolved with different diffusion coefficient values and different boundary conditions. Tate uses unrationalized CGS-ESU.

D [cm^2/s] := diffusion coefficient ($D = D_+ = D_-$); d [cm]:= electrode separation distance

$j_\pm$ [statA/cm^2] := ± current density, $j = j_+ + j_-$

k [cm^2/statV·s] := ion mobility ($k = k_+ = k_-$) where $k \approx 300\mu$, μ [cm^2/V·s]

$n_\pm$ [/cm^3] := ±ion density, n_{ss} [/cm^3] = $(q/\alpha)^{1/2}$:= steady-state ion density

q [/cm^3·s] := ionization rate; s [cm] := distance from center of cell, $0 \le s \le d/2$

v [] = $n_+/(q/\alpha)^{1/2} = n_+/n_{ss}$:= normalized +ion density

w [] = $n_-/(q/\alpha)^{1/2} = n_-/n_{ss}$:= normalized –ion density

y [] = $2ek(q/\alpha)^{1/2}E/j = 2ekn_{ss}E/j$:= scaled electric field

α [cm^3/s] := ion-ion recombination coefficient

τ [t] = $(\alpha q)^{-1/2}$:= mean ion lifetime when recombination in equilibrium with production

τ_D [t] = $d^2/4D$:= characteristic diffusion time of the chamber,

τ_d [t] = d^2/kV := ion transit or drift time across chamber (Tate uses T instead of τ_d)

* PA Tate, Effect of Diffusion on the Saturation Curve of a Plane Parallel Ion Chamber, Phys Med Biol, 11(4) (1966) 521-532

Ion Drift and Diffusion Time-Constants

- **The drift velocity, v_d, of an ion is $v_d = \mu E$ cm/s so that in a constant electric field, E, the travel time between electrodes is $\tau_d = d/|\mu E|$ s**
- **The diffusion velocity, $|v_D|$, of an ion is $|v_D| = (D/n)$ grad n cm/s, however, there are two different ion diffusion times for plane-parallel electrode geometry that are used by different authors**
  - **Tate** $\tau_D := d^2/4D$
  - **McDaniel** $\tau_D := d^2/\pi^2 D$
- **The half-life, $\tau_{1/2}$, of an ion when ionization is in equilibrium with recombination is $\tau_{1/2} = 1/n_{ss}\alpha = 1/(q/\alpha)^{1/2}\alpha = (\alpha q)^{-1/2}$ s;**
  - **let $\alpha \approx 1 \times 10^{-6}$ cm^3/s then for different ionization rates, q**
  - **q=10^{10}: $\tau_{1/2}$ = 10 ms, q=10^{12}: $\tau_{1/2}$ = 1 ms, q=10^{14}: $\tau_{1/2}$ = 0.1 ms**

Consider a plane-parallel electrode cell with either air or H_2 gas and electrode separation distance d = 0.1 cm
NTP is 293.15 K (20 °C) and p = 101.325 kPa (1 atm)
Einstein relationship: $D = \mu k_{eV} T$, $k_{eV} \approx 0.86173 \times 10^{-4}$ eV/K and $k_{eV}T|_{T=300} \approx 25.852$ meV
For H_2 gas* $\mu_+|_{T=300K} \approx 10.2$ cm^2/V·s and $D_+|_{T=300K} = \mu_+ k_{eV} T|_{T=300K} \approx 263.69 \times 10^{-3}$ cm^2/s
Tate: $\tau_D := d^2/4D_+ = (0.1 \text{ cm})^2/4(263.69 \times 10^{-3} \text{ cm}^2/\text{s}) \approx 9.5$ ms
McDaniel: $\tau_D := d^2/4D_+ = (0.1 \text{ cm})^2/\pi^2(263.69 \times 10^{-3} \text{ cm}^2/\text{s}) \approx 3.8$ ms
Thus, when ionization is in equilibrium with recombination the loss of ions by recombination, before they can diffuse to the electrodes, depends on the rate of ionization of the gas. As these equations show, reducing the separation distance, d, reduces the diffusion time but with fewer total number of ions available in the gas.

* G Sinnott, Mobility of Ions in Hydrogen, *Phys Rev* **136**(2A) 1964, 370-375

Estimating Ion Density, *n*, as a Function of *q*

- Consider the case of a gas containing only one type of positive and negative ion
- Let $q_+ = q_- = q$ and $n_+ = n_- = n$ with $E = 0$, $i = 0$, and no diffusion
  - From the charge conservation equations, $dn/dt = q - \alpha n^2$ with initial condition $n = 0$ at $t = 0$ the solution is
  - $n = (q/\alpha)^{1/2} \{\exp[2(q/\alpha)^{1/2}\alpha t] - 1\}/\{\exp 2[q/\alpha)^{1/2}\alpha t] + 1\}$
  - Then as t approaches infinity the steady-state ion density, n_{ss}, becomes
  - **$n_{ss} = (q/\alpha)^{1/2}$ with $\alpha \approx 1 \times 10^{-6}$**
- Thus, the potential recoverable-number of ions can increase by approximately 3-orders of magnitude if recombination is minimized

This result indicates that increasing the rate of ionization can insignificantly increase the number of available ions, n_{ss} to harvest and thus could improve LEC performance and output power. As shown, this parameter is involved in scaling up LEC output.

Increase Diffusion of the Ions, $D_{\pm}d^2n_{\pm}/dx^2$

- Modify the diffusion coefficient, $D_{\pm} = \mu_{\pm}(k_B/e)T$, by increasing the temperature of the gas in the LEC
  - **Improvement of approximately 5/3 going from 300 K to 500 K**
- Change the diffusion to ambipolar diffusion by reducing the amount of electronegative gas, O_2, so that electron attachment is reduced and more of the negative ions are free electrons where $\mu_e >> \mu_i$
  - **Ambipolar diffusion coefficient, $D_a = (\mu_i D_e + \mu_e D_i)/(\mu_i + \mu_e)$ where $\mu_e >> \mu_i$ gives an improvement factor of approximately 2**
- At low values of the electric field, E, and recombination $\alpha n_+ n_-$
  - $d^2n_{\pm}/dx^2 \approx -q_{\pm}/D_{\pm}$

These changes in fabrication and operation could improve LEC performance. As shown, these parameters are involved in scaling up LEC output.

Quo Vadis LEC?

- **The question of 'whither goest thou LEC?' is critically important at this time of 'climate crisis' and concerns over CO_2 emission**
- **Although a LEC currently only produces a few microwatts of power, it is clear from the analysis that several orders of magnitude improvement are possible per square centimeter of projected surface area.**
- **The LEC represents a direct conversion of non-chemical energy into electricity that operates 'day and night', 'rain or shine', or 'whether the wind blows or not'**
- **It is estimated that if a LEC could light only LEDs it would help reduce fossil energy use and thus CO_2 emission in many 3rd world countries**
- **Collaborative assistance from Universities and Industry could accelerate scaling up the power of a LEC a pathway to future 'green energy'**

Perhaps the most important observations that points 'the way' to future development of LEC devices as potential sources of 'green energy' are that, even without an understanding of the nature of the gas ionization process, LECs are based on well established physics and do not use materials that are naturally radioactive.

Summary of LEC Characteristics

- **CPD conduction is a real electrophysical (ion migration) phenomenon**
- **LEC devices behave like current sources at low cell voltages**
- **Maximum LEC power occurs when ion diffusion matches ion drift**
- **Maximum LEC voltage is the CPD of the electrode's work functions**
- **There is no analytic solution for the electric field within the gas**
- **There is no analytic solution for the ion distribution within the gas**
- **Electrode separation is the most probable optimization variable**
- **There are many opportunities to increase LEC design power output**

A LEC device is a new and novel electrical power producing device based on the contact potential difference (CPD) between dissimilar metal electrodes and the diffusion of mobile ions in an electrolyte between the electrodes. A LEC device uses no external electrical or electromagnetic input nor any materials that are normally considered to be radioactive. When a gas is used as the electrolyte the source and nature of the process that ionizes gas is still unknown. However, LEC devices are easily constructed and there have been multiple independent replications of their performance. Electrically, LEC devices behave as current sources with an 'open circuit' voltage of the CPD of the electrode's work functions. Currently, gaseous electrolyte LECs have be constructed using electrodeposited palladium (Pd) or iron (Fe) thin films or electrodeposited Pd particles with either hydrogen (H_2) or deuterium (D_2) gas. In contrast to most gaseous electronic devices (GEDs), such a ionization chambers operating at high voltage (> 100 V), diffusion of the ions in a LEC predominates over electric field induced drift. Thus, since a LEC conducts by diffusion the conduction processes in a LEC need to be analyzed in order to optimize performance and increase LEC power output. Many power optimization possibilities exist and, with commercial development, LEC devices could provide a source of both 'green' and CO_2 emission free energy for the future.

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