PREPRINT

The Lattice Energy Converter (LEC), an Electrophysical Direct Energy Converter (EDEC)

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Abstract

A Lattice Energy Converter (LEC) is a direct energy converter to electricity that will self-initiate and self-sustain the production of a current through and a voltage across a load impedance without the use of naturally radioactive materials or external electrical input. The initial LECs used a gas electrolyte in conjunction with 'active' hydrogen-occluded hydrogen host materials such as electrodeposited palladium and iron. Based on an improved understanding of the mechanisms involved, it is recognized that a LEC is the forerunner of a type of device within the larger group of devices that take advantage of the electrophysical properties of different materials and cell configurations to produce an Electrophysical Direct Energy Converter (EDEC). EDECs with 'active' materials have experimentally demonstrated the use of several different electrolytes, carefully selected to minimize electrochemical reactions, to transport charge including self-ionizing liquids, gels, solids, and even solid-state photovoltaics to produce electricity. A model of a gaseous LEC is presented based on known physics to explain the experimental results.

Key Words: Direct energy conversion, Lattice Energy Converter, Electrophysical Direct Energy Converter, Contact electrification

1. Introduction

As previously reported [1-3], a Lattice Energy Converter (LEC) -is a device including two or more electrodes with different work functions, that without any electrical input, will spontaneously and continuously convert thermal energy, metallurgical energy, such as the potential energy of a strained lattice due to its deformation because of occluded hydrogen, or quantum energy into an electrical output which is characterized as time averaged direct current that appears to be produced by multiple discrete events within the lattice of the 'active' hydrogen-occluded hydrogen host materials. The emission of electrons is also considered possible by the impact of fast-moving gas ions on the high work function (HWF) electrode when the HWF electrode is in contact with 'active' hydrogen-occluded hydrogen host material (HHM) such as iron (Fe) or palladium (Pd) electrodeposited from a aqueous solution.

When a medium such as an electrolyte is in contact with the high work function HWF and low work function (LWF) electrodes, experimental results include the ability to produce approximately 7 X 10^{14} electrons per second, per square centimeter of electrode surface area between the electrodes. By comparison, a nuclear battery would require the equivalent of hundreds to thousands of curies of radiation to produce this much current. By studying the history of discoveries in electricity including contact electrification, a model is developed that explains the currents produced by a gaseous electrolyte LEC and indicates alternative materials that will provide the functions of a non-gaseous electrolyte. Based on this knowledge, it was realized that the gaseous LEC is just one device of a group of Electrophysical Direct Energy Converter (EDEC) devices which can use gases, self-ionizing liquids, gels, solids, and solid-state photovoltaics such as photocells to transport charge between the electrodes. An electrophysical LEC/EDEC is different from a typical battery,

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that produces electricity based on electrochemical reactions, since the power dissipated internally in a LEC/EDEC goes to zero when a LEC is shorted and its voltage goes to zero.

2. Background

Electricity has been studied for several thousand years [4]. A few selected discoveries that contribute to the development and operation of a LEC or an EDEC device are included as background. Additional authors and comments are presented in the Appendix in [3] entitled "From Volta to the LEC: Important Events in Their Own Words with Emphasis Added."

Around 600 BCE, a Greek mathematician and philosopher, Thales of Miletus (c 624–546 BCE) discovered the basic principle of triboelectric static electricity when he rubbed a rod made of amber with fur and found that it attracted light objects, such as bits of feathers. Since that discovery, multiple uses have been made of the triboelectric or a related effect, such as the development of an "electron attachment" by a metal surface in the presence of a flowing gas. In the case of a gaseous electrolyte LEC, Landa patent application [5] observation is one possible explanation of how electrons are removed from the high work function electrode and exchanged into the electrolyte.

Englishman Sir William Watson (1715–1787) developed the concept of a closed path electric circuits around which charge flows under the influence of an electrical potential difference called a voltage; and the American Benjamin Franklin (1706–1790) confirmed that there were two types of charges which he named "positive" and "negative." These are the two types of ions that are important in the LECs electrolyte. Franklin also conducted his famous kite experiment in 1752 when he demonstrated the electrical nature of lightning by flying a kite during a thunderstorm. Franklin's observations led him to propose the idea of the lightning rod. It is now known that for a given charge distribution, the sharper the object, the greater the electric field at the surface of the sharp point [6]. In addition, if the small radius sharp point of the 'active' hydrogen-occluded HHM is negatively charged, it is possible for electrons or whatever the "new" form of 'unknown agency' radiation that fogs the film in the SPAWAR [7] or BARC [8] experiments, to be emitted from the 'active' surface which may play a role in the implementation of EDEC devices. Experiments have shown that electrodes that include 'active' hydrogen-occluded hydrogen host material particulates on their surface produce more power due to their small size, their 'activity', and an increase in electrons in the conduction band of the material. An alternative explanation is that electrons are emitted by the HWF electrode in a manner described by E Storms [9] however, the reported results are inconsistent with the experimental data presented herein.

While studying the contact potential difference of materials, Italian physicist Alessandro Volta (1745–1827), published in 1800 that when two dissimilar metals are brought into electrical contact with each other and then separated the two materials will have redistributed their charge carriers and produce different deflection of the leaves of an electroscope depending upon which of the contacted metals was measured [10-11]. In modern terminology Volta connected two metals with different work functions and observed a contact potential difference (CPD) by inference from the electroscope readings.

Although Volta was initially studying contact electrification, he accidentally discovered electrochemical reactions that were produced when different materials such as silver and zinc were separated by pieces of cardboard soaked in saltwater or lye. This discovery led to the invention of the electrochemical battery—an important invention that revolutionized the history of electricity. However, this invention diverted attention from contact electrification which is a primary feature in the operation of LECs and EDECs.

Scottish chemist Thomas Graham, FRS, (1805–1869), was the Master of the [Royal] Mint from 1855 until his death. During his tenure, he conducted experiments with rare metals, including palladium, and created at least two hydrogen loaded palladium medallions [12]. In 1863, Henri Sainte-Claire Deville and L. Troost showed that hydrogen diffused rapidly through homogeneous plates of high-temperature iron and platinum. Graham showed that palladium became permeable to hydrogen at 240 °C and at a slightly higher temperature the rate of diffusion was several cc per minute. Graham used the word "occluded" to differentiate how hydrogen atoms are positioned in the palladium (Pd) lattice. Unlike metal hydrides which are compounds formed by metals that are covalently bonded with hydrogen, the hydrogen atoms that are occluded in the lattice contribute electrons to, and greatly increase, the number of electrons in the conduction band of the material which is important for the LEC and EDEC devices.

In 1873, Scottish physicist and mathematician James Clerk Maxwell (1831–1879) published a complete theory of electromagnetism, neatly summarizing everything that was then known about electricity and magnetism. Maxwell teamed with Austrian mathematician and physicist Ludwig Boltzmann (1844-1906) to develop equations describing the statistical distribution of velocity or energy among gas molecules at a specific temperature, and derived the formulae known as the Maxwell-Boltzmann distributions. For a gaseous LEC at normal temperature and pressure, these equations predict that the number of gas molecules impacting a square centimeter of electrode surface is approximately 1.4 x10^{24} per second as well as the energy distribution of the impacting ions. The impact of gas molecules and ions, in the absence of 'active' material, the current is the same in both directions. However, in the presence of 'active' material there are more electrons being transported from the HWF electrode to the LWF electrode than in the opposite direction.

In 1896, English physicist and Nobel Laureate Joseph John Thomson (1856–1940), and New Zealand physicist, Nobel Laureate, and British peer Ernest Rutherford (1871–1937), published on the conduction of electricity through gases that were being ionized by Röntgen rays (X-rays) or by radiation from radioactive materials [13]. They observed, that for a cell with plane-parallel electrodes including an increasing external voltage source, the current produced by a gas exposed to external radiation "saturates" at a value equal to the product of the rate of ionization of the gas, q, times the elementary electron charge, e, and the separation distance of the electrodes, d, *i.e.*, $I_{\text{sat}} = qed$. However, the current produced by multiple InovL experiments with gaseous LEC cells containing 'active' hydrogen-occluded hydrogen host materials (HHMs) does not "saturate" when subjected to an increasing external voltage.

Thomson published that a gas only conducts electricity when it contains gaseous ions [14]. This observation is the basis of the exchange and transport of charge produced by a LEC with a gaseous electrolyte and its extension to other EDEC devices using electrolytes such as self-ionizing liquids, gels, and solids that contain mobile ions. The presence of mobile ions may not be enough, because these ions must be able to be discharged on the electrodes. When a piece of metal is immerged in an electrolyte, a double layer of ions accumulates at the surface, but they are not discharged because this double layer of ions is stable. The ions can only be discharged if a sufficient external voltage is applied (electrolysis) or the ions react with the metal (electrochemical battery).

In 1903, the German experimental physicist, Eduard Riecke (1845–1915) published a complete set of equations that include both terms for ion concentration gradient induced ion diffusion as well as the electric field induced ion drift [15]. For most researchers, diffusion has been ignored as being insignificant although it is ion diffusion that is the driving force behind the spontaneous current produced by LEC and EDEC devices at low values of load resistance.

In 1916, an American Nobel Laureate chemist, physicist, and metallurgical engineer, Irving Langmuir (1881–1957) published descriptions of experimental results [16] where he showed that it was possible to conduct a current between dissimilar electrodes possessing a contact potential difference (CPD) as long as the dissimilar electrodes were in contact with a gas that was ionized by a source of radiation, and that the energy for the conduction of the electricity was supplied by the energy necessary to maintain the ionization of the gas. In the case of a LEC or an EDEC, based on electrophysical properties and the selection of the 'active' hydrogen-occluded hydrogen host materials and electrolytes, an external ionization source is not required. In fact, InovL experiments suggest the 'active' hydrogen-occluded HHM may act as the ionization source.

In 1932, an American physicist, Karl K Darrow (1891–1982) published a treatise where he described the conduction of ions under both the influence of ion density gradients (ion diffusion) and an electric field (ion drift) [17]. Also, Darrow recognized that due to the diffusion terms in the equations, the current-density conduction equation predicts conduction where the voltage and current-density don't need to go to zero together. Additionally, the ion-diffusion terms and the ion-drift terms make opposing contributions to the power delivered to an external load impedance that causes maximum produced power to occur at an intermediate value of load impedance somewhere between a 'short circuit' and an 'open circuit.' This is why it is important to measure the load voltage at several different load impedances when characterizing a LEC or EDEC device since direct current (DC) load power is device load voltage squared divided by load resistance.

Italian and naturalized American Nobel Laureate Enrico Fermi (1901-1954) was known for his work in quantum physics. Among his discoveries are the Fermi levels and Fermi energies of different materials. The Fermi level is a measure of the energy required to remove the least tightly held electrons within a solid which is important in determining the electrical and thermal properties of solids. When two materials with different Fermi levels are in electrical contact, their Fermi levels will equilibrate to a state where one material has more electrons, and the other has fewer electrons than their original states. Fermi's observations formalized Volta's observations and explained Langmuir's descriptions of contact potential difference (CPD) and the charge equilibration process. Along with the use of 'active' material and the application of the Maxwell-Boltzmann statistics, these observations form the basis for a model that is key to understanding the production of electrical current by a LEC or an EDEC.

In 1989, British electrochemist Martin Fleischmann, FRS, (1927-2012) and American electrochemist Stanley Pons (1943-present), announced that they had performed electrolysis experiments with palladium metal and heavy water (D_2O), that produce more heat than that which could be accounted for from chemical reactions, leaving open the possibility that nuclear reactions might be involved [18]. Although originally known as 'Cold Fusion,' it is more appropriately known as Low Energy Nuclear Reactions. (LENR) within the broader field of Condensed Matter Nuclear Science (CMNS). Although LENR has not been established as the source of the activity of hydrogen-occluded hydrogen host material used in LEC or EDEC devices, it may play a key role in the increased cell performance observed when it is used in LECs and EDECs.

3. LEC and EDEC descriptions, experimental results, and analysis:

In its simplest implementation, a contact electrification device consists of two or more electrodes of different work functions and Fermi levels, connected together through an electrical impedance and a charge exchange and transport medium (electrolyte). The transport medium lying in electrical contact with the electrodes such that there is a continuous transfer of electrons from the low work function electrode through the electrical connection to the high work function electrode, followed by charge exchange at the high work function electrode and transport back to the low work function electrode through the electrolyte. As observed by experimentation, the electrolyte can be an ionized gas, a self-ionizing liquid or gel, or even a solid material that contains mobile ions. A solid-state material such as a semiconductor or a p-n junction photovoltaic has been used in place of an electrolyte. Care should be taken that the charge transport and exchange medium does not react chemically with the cell materials. This is the major consideration for the EDECs. Whereas most prior research has focused on the drift of ions due to the electric field and minimized diffusion due to concentration gradients, a LEC or an EDEC takes advantage of both drift and diffusion to produce a voltage, current, and load power. When an 'active' hydrogen or deuterium-occluded hydrogen host material such as electrodeposited palladium (Pd), nickel (Ni) or iron (Fe) or their particulates is deposited on the high work function electrode or added to the electrolyte of a LEC or an EDEC, the electrical power output produced is significantly increased.

A lattice energy converter (LEC) or electrophysical direct energy converter (EDEC) can be implemented in multiple configurations for test and evaluation purposes. Figure 1 shows an EDEC configuration that is particularly easy to implement and test.

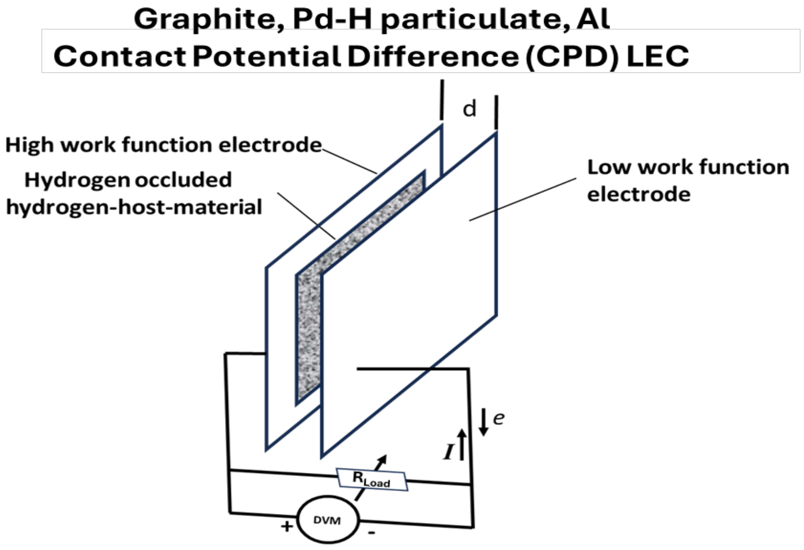


Figure 1 shows a plane-parallel electrode implementation of a contact electrification device or cell exploiting the Contact Potential Difference (CPD) between graphite, HWF and aluminum, LWF electrodes. When optional hydrogen-occluded hydrogen host material is located between the electrodes the contact electrification device or cell becomes a LEC or an EDEC depending on the type of electrolyte used. A variable load resistor is connected to the high work function electrode so that the voltage and thus the current as well as the power delivered to the load can be measured. Not shown is the electrolyte that is in contact between the two electrodes.

Figure 2 is a log-log plot of an InovL experimental gaseous LEC cell similar to that described in Fig. 1. In Fig.2, a digital voltmeter (DVM) measured the spontaneous voltage and current produced by a H_2 gaseous electrolyte LEC with a low work function counter electrode (CE) of aluminum (Al) and a high work function working electrode (WE) of carbon (C) where electrodeposited palladium (Pd) particulate that had been salvaged from a light water (H_2O) plating procedure. Let S be the common area of the two electrodes, then when cell voltage, V_{DVM}, cell current, $I_{\mathrm{cell}} = V_{\mathrm{DVM}}/R_{\mathrm{load}}$, and load power-density, $P_{\mathrm{load}}/S = (V_{\mathrm{DVM}}^2/R_{\mathrm{load}})/S$, are plotted in a log-log plot versus load resistance, R_{load}, three distinct operating regimes become apparent. These regimes are labeled diffusion regime, maximum power regime, and drift regime.

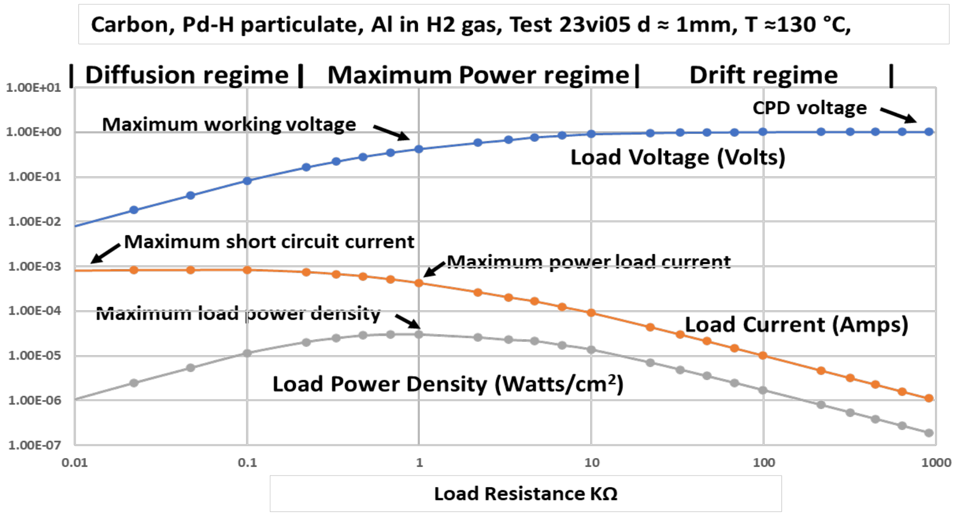


Figure 2 is a log-log plot of the three distinct operating regimes of a plane-parallel electrode gaseous electrolyte LEC with an aluminum low work function electrode, palladium (Pd) particulate hydrogen host material in contact with a carbon (C) high work function electrode. The electrodes are separated approximately 1 millimeter, and the working temperature is approximately 130 °C. The surface area of the electrodes is approximately 6 cm^2 and the ordinate is the value of the voltage, current, or power of the cell.

At low values of load resistance, the load voltage (blue trace) increases as the load resistance increases but becomes asymptotic to the contact potential difference (CPD) of the Al-C electrodes at high values of load resistance. At low values of load resistance, the load current (red trace) is approximately constant indicating that the LEC acts as an ion diffusion driven current source. At high values of load resistance, the load current decreases with increasing load resistance indicating that there is a variable voltage ion drift shunt current in parallel with the load current. Thus, it is at intermediate values of load resistance that the LEC delivers its maximum power-density (green trace) to the load.

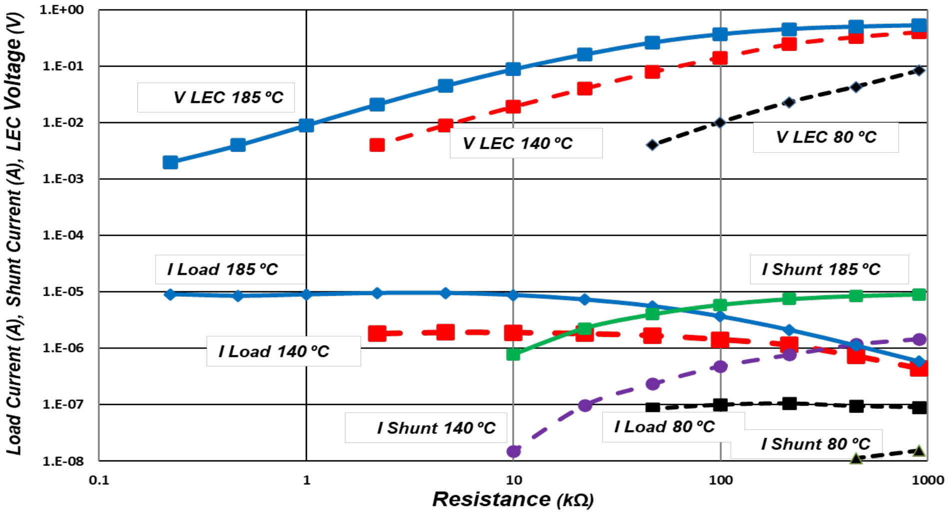


Figure 3 shows a combined log-log plot of measured LEC voltages and calculated currents through the LEC's load resistor as a function of load resistance at three different temperatures of 80 °C, 140 °C, and 185 °C for a concentric cylindrical Pd on Cu HWF electrode and a galvanized Zn LWF electrode in hydrogen gas with no external electrical energy supplied to the cell. [1-3]

At low values of load resistance, the cell is operating in the diffusion regime and load current is approximately constant. At intermediate values of load resistance, the cell voltage is increasing but the current is constant so that the power delivered to the load resistance, *i.e.*, cell voltage times load current, is increasing. However, in the drift regime at high values of load resistance, ion drift due to the electric field in the cell produces a voltage variable shunt current internal to the cell so that the power delivered to the load now decreases.

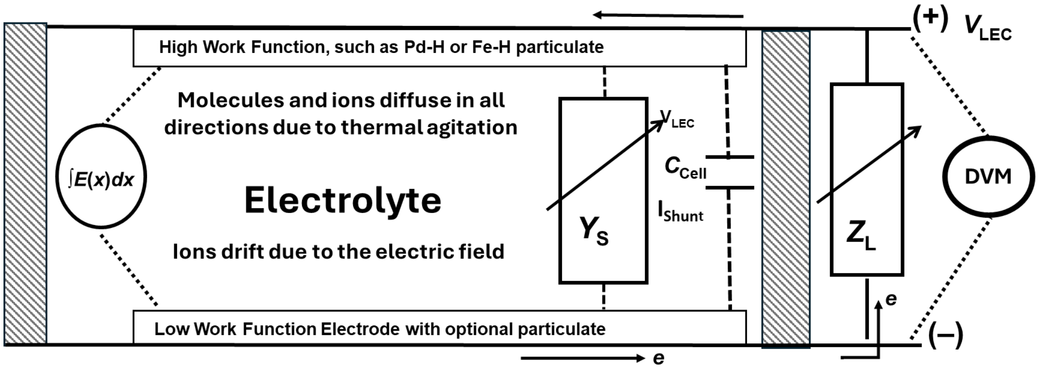


Figure 4 is a phenomenological equivalent circuit of a LEC or an EDEC. A variable voltage admittance, Y_S, shunts the load impedance, Z_L, and the voltage between the electrodes is the integral of the electric field, E, between the high work function electrode and the low work function electrode.

In Fig. 4, the variable admittance Y_S is included in the phenomenological equivalent circuit to account for the shunt current shown in Fig. 3. This shunt current is the result of the electric field induced drift of the ions reducing the number of diffusion charges that reach the high work function electrode due to its positive polarity.

Similar multi-regime load power behavior has been observed for EDEC devices where the material in contact with the electrodes is a self-ionizing liquid, a gel, or even a solid if there are mobile ions present so that the material behaves as an electrolyte. A possible explanation of these observations may be summarized in the following manner. Two or more electrodes with different work functions and Fermi levels are required. A load impedance, Z_L, in contact with the electrodes provides a means of contact electrification whereby the low work function (LWF) electrode *transfers* electrons through the load impedance to the high work function (HWF) electrode to equilibrate the different Fermi levels of the electrodes. Upon equilibration of the Fermi levels of the electrodes, a contact potential difference (CPD) equal to the difference in the work functions of the electrodes divided by the elementary charge, $V_{CPD} = (\Phi_{HWF} - \Phi_{LWF})/e$, is formed between the electrodes. When there is an energetically 'active' material, such as hydrogen-occluded electrodeposited palladium (Pd) or iron (Fe) hydrogen host material (HHM) in contact with the HWF electrode, charges are *ex*changed at the interface with the electrode. This results in the *transport* of charge from the HWF electrode to the LWF electrode thus completing the electrical circuit of the LEC or EDEC so that more charge can be *transferred* from the LWF to the HWF electrode.

Note that two different time scales are involved in the operation of a LEC or an EDEC. The transfer of charge from the LWF to the HWF electrode is fast, occurring at near the speed of light in the conductor and the load impedance connecting the electrodes. The *transport* of charge from the HWF to the LWF electrode is slower and determined by the diffusion of charge [19-20] in the mobile ion material or electrolyte in contact with the electrodes. Additionally, there is an activation energy threshold associated with the *exchange* of charge at the electrode-electrolyte interfaces which accounts for the variation of the power delivered to the load impedance that depends on the operating temperature of the LEC or EDEC.

Exchange of charge at the electrode-electrolyte interface can occur by several different methods. Electrons can be emitted by the HWF electrode due to electric field emission at charge concentrations due to surface roughness of the electrode or to particulate matter deposited or in contact with the electrode. Electrons can be removed by ion impact from the 'active' material of the HWF electrode by triboelectric contact [1-3, 7]. Electrons also can be emitted by the HWF electrode by quantum effects such as the illumination of the electrode by high energy light via the photoelectric effect, or possibly by LENR activity of 'active' hydrogen host material in proximity to the HWF electrode. Additionally, charge neutralization can occur at the electrode when a charged electrolyte molecule *exchanges* charge with an image atom at the surface of the electrode to become a neutral molecule in the charge *transport* material. There is an activation energy associated with charge neutralization since the ion and the electrode both have the same charge and repel the ion as it approaches the electrode.

The kinetic theory of gas [19] and a similar theory for the case of a self-ionizing liquid, gel, and solid electrolytes can explain the experimentally measured current densities of LEC and EDEC devices.

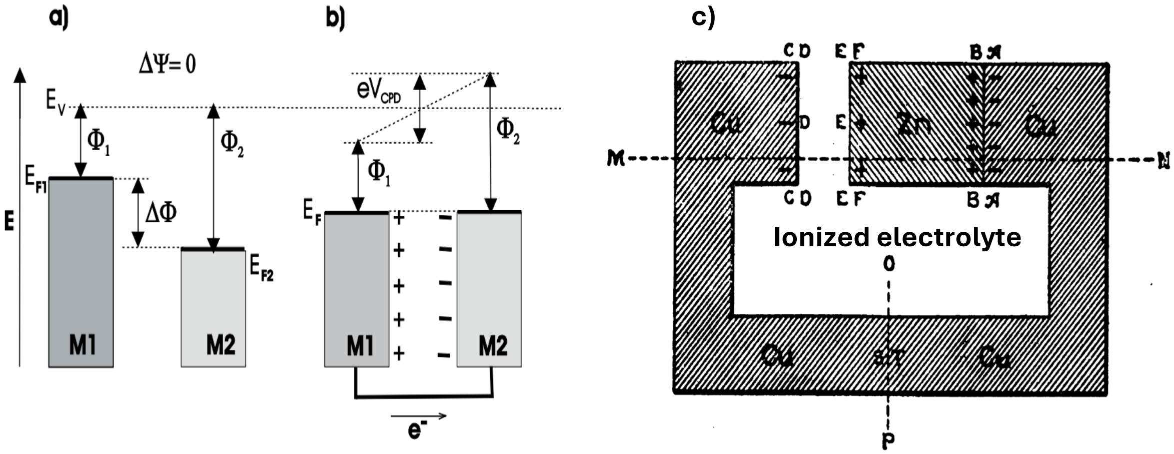
In the case of a gaseous electrolyte, the molecules and the ions in the gas are in continuous stochastic motion with some of the molecules and ions impacting the electrodes at all times. Figures 10, 11, and 12 show the Maxwell-Boltzmann energy curves and the molecular speed curves for hydrogen gas as a function of gas temperature. As the temperature of the gas increases, more molecules and ions have increased energy and thus, can overcome the work function energy of the 'active' HHM charge exchange process at the working electrode's electrolyte interface.

In particular, at normal temperature and molecular density, the number of electrode or wall impact is of the order of 10^{24} impacts per square centimeter of surface area per second. If just one in a billion of these electrode or wall impacts results in the exchange of a single electron, then the number of impacts is sufficient to explain the experimentally measured current densities of charge flowing in the load impedance of a LEC or an EDEC. Additionally, the number of electrode impacts increases linearly with the number density of the gas and thus the initial filling pressure of a gaseous LEC influences the amount of maximum power delivered to the load impedance.

4. Contact electrification

There are several different energy levels associated with a metal or a semiconductor. Antoine Kahn writes [21]:

> Fermi level (E_F) and vacuum level (E_{VAC}) [E_V] positions, [and] work function (WF) [Φ] are parameters of great importance for any electronic material, be it a metal, semiconductor, insulator, organic, inorganic or hybrid. To a large extent, these parameters are key ingredients that define the electronic structure of all interfaces between a material and the outside world, and control processes of charge exchange and transport across interfaces in all electronic devices. However, they are also subject to significant variations between samples of the same material. ⋯.
>
> In a sense, the work function WF = $E_{VAC} - E_F$ represents the energy barrier to free space that prevents an electron at the Fermi level from escaping the solid. This barrier, which culminates at E_{VAC}, consists of two components, a bulk component and a surface component. WF is measured as the combination of the two components, which cannot be experimentally separated.



O Vilitis *et al*, 2016 [22]

I Langmuir, 1916 [16]

Figure 5a shows two metals (M1, M2) with Fermi levels (E_{F1}, E_{F2}) and work functions (Φ_1, Φ_2) with no electrical connection between the two metals. Figure 5b shows the same two metals after interconnection with a wire. The Fermi levels of the two metals have equilibrated and now there is a contact potential difference (CPD) between their surfaces equal to the difference in work functions, $\Delta\Phi/e$. Figure 5c shows a copper (Cu) metal in contact with a zinc (Zn) metal including a gap (CD, EF) between the metals and an ionized gas electrolyte in the gap.

In Fig. 5a there is no electrical connection between the metals M1 and M2. The Fermi levels (E_{F1}, E_{F2}) are unequal and there is no difference in work function at the vacuum energy level, E_V. of their surfaces. Figure 5b shows the two metals connected by a wire in which electrons, e^-, have now flown from the low work function metal, M1, to the high work function metal, M2, until their Fermi levels have equilibrated at an intermediate energy value of E_F. Thus, there is now a difference in work functions at the vacuum energy level, E_V, that gives rise to a contact potential difference, $V_{CPD} = \Delta\Phi/e = [\Phi_{\text{high WF }(\Phi 2)} - \Phi_{\text{low WF }(\Phi 1)}]/e$. In addition, there is now an excess of charge (-) on the surface of metal M2 and a deficiency of charge (+) on the surface of M1. This CPD now prevents any more charge flowing from M1 to M2. If there exists a means of neutralizing or transferring charge from the surface of M2 to an intermediate material between the two metals and then to M1, a sustained continuous flow of electrons from M1 to M2 would be possible. Indeed, this sustained current is possible to achieve. Figure 5c shows an arrangement of electrodes of zinc (Zn) and copper (Cu) connected together with an ionized gas electrolyte between the electrodes.

Langmuir analyzed the gas electrolyte arrangement, and in 1916 published a paper [16] stating that the energy needed to sustain the current is supplied by the energy necessary to maintain the ionization of the gas. This energy can be supplied by a source of ionizing radiation such as Röntgen rays (X-rays), or radioactive particle emission as described by JJ Thomson and E Rutherford [13] or by ultraviolet (uv) light as was reported by Ohmart in his experiments [23] on a self-powered radiation detector.

A liquid electrolyte electrophysical phenomenon was observed in an InovL experiment using a low work function electrode of aluminum (Al), a high work function electrode of copper (Cu), with flyscreen separating the approximately 500 cm^2 electrodes. Figure 6 shows an example load test of an EDEC cell using the self-ionizing properties of ethylene glycol [24] as the mobile ion containing electrolyte. However, when using a liquid or gel electrolyte that contains hydroxyl ions, $(OH)^-$, care must be taken to avoid chemical reactions such as the reaction $Zn + 2(OH)^- = Zn(OH)_2 + 2e^-$ which consumes the zinc (Zn) electrode by converting it to insoluble zinc hydroxide, $Zn(OH)_2$. This hydroxyl ion chemical reaction explains the increased electricity produced in A Volta's experiments on contact electrification when he substituted Zn for tin (Sn) as his low work function electrode and accidentally discovered the forerunner of the electrochemical battery.

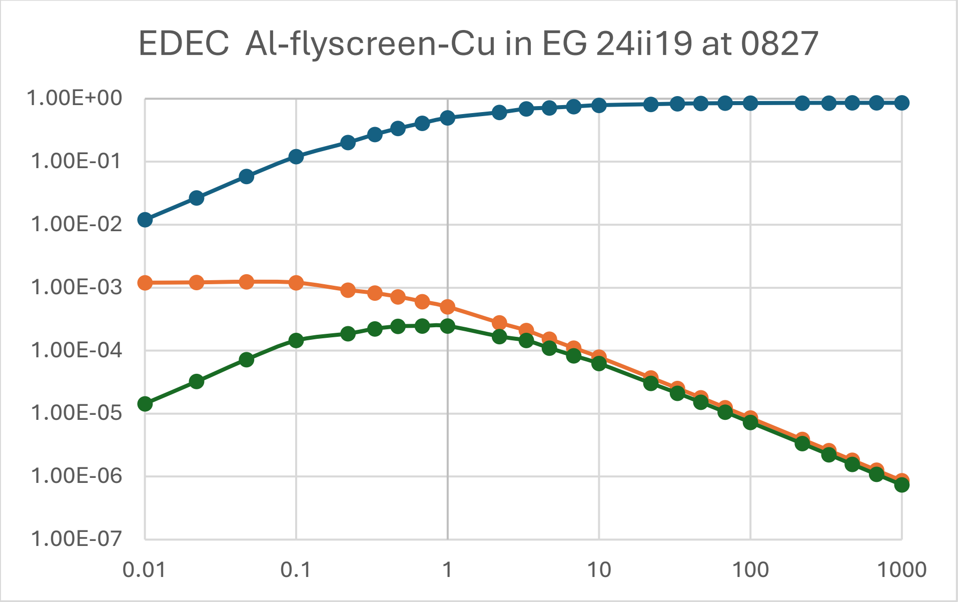


Figure 6 shows a log-log variable resistance, R_{load} = 0.01 kΩ to 1000 kΩ, load test of an EDEC cell using ethylene glycol as the cell's electrolyte. The blue trace is cell voltage, V_{cell} V. The red trace is EDEC current, I_{cell} A. The gray trace is cell power, $P_{cell} = V_{cell}^2/R_{load}$ W.

Figure 6 shows a load test of an EDEC made from an aluminum (Al) low work function electrode, an insulating separator made of flyscreen, and a copper (Cu) high work function electrode. The electrolyte was self-ionizing ethylene glycol although non-toxic propylene glycol also will work [18]. These electrolytes will spontaneously self-ionize by molecule-to-molecule interaction with one molecule acting as an acid to become a positive ion and the other molecule acting as a base to become a negative ion. A small contribution to the current possibly results from the slow corrosion of the aluminum plate. However, electrolytes containing ethylene glycol are used in electrolytic capacitors that have aluminum electrodes with only a small degradation after 30 years of service.

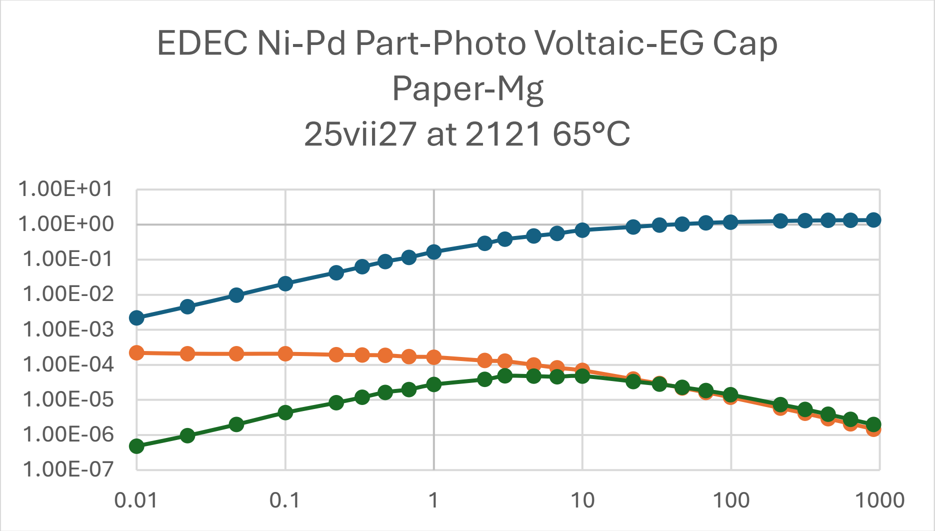


Figure 7 shows a log-log variable resistance R_{load}= 0.01 kΩ to 1000 kΩ load test of an EDEC cell using photovoltaic and ethylene glycol capacitor paper as the cell's electrolyte. The blue trace is cell voltage, V_{cell} V. The red trace is EDEC current, I_{cell} A. The gray trace is cell power, $P_{cell} = V_{cell}^2/R_{load}$ W.

Figure 7 shows a load test of an EDEC made from a magnesium (Mg) low work function electrode, an insulating separator composed of glycol impregnated capacitor paper, photovoltaic, palladium (Pd) particulate, and a nickel (Ni) high work function electrode. The electrolyte was self-ionizing ethylene glycol impregnated paper [25] although non-toxic propylene glycol also will work. [24] These electrolytes will spontaneously self-ionize by molecule-to-molecule interaction with one molecule acting as an acid to become a positive ion and the other molecule acting as a base to become a negative ion.

Contact electrification of metals and semiconductors with the resulting generation of a contact potential difference (CPD) or Volta potential is one of the most important differences between LEC and EDEC devices and the types of gaseous electronic devices (GEDs) studied by JJ Thomson and others at the Cavendish Laboratory of Cambridge University in the late 1890s and early 1900s. The properties of conventional GEDs are described in detail in L Lobe's 1960 treatise [26].

5. Modelling the gaseous LEC and the evolution from the LEC to the EDEC

The knowledge learned in analyzing the LEC is important to understand the larger group of Electrophysical Direct Energy Conversion devices. Herewith is the model for a gaseous LEC. The conduction of electricity through gases was an important topic in the latter years of the 19th century. A Shuster writes in 1884 [27]:

> ⋯ that the conduction of electricity through gases is more probably due to something resembling the electrolytic conduction of liquids than to the direct passage of electricity than from one molecule to another.

in 1899 JJ Thomson, director of the Cavendish Laboratory at Cambridge University, provides a proper explanation for the electrical conduction of gases when diffusion of the ions can be neglected [29]:

> The electrical conductivity possessed by gases under certain circumstances— ··· —can be regarded as due to the presence in the gas of charged ions, the motions of these ions in the electric field constituting the current.

In 1903, German experimental physicist, E Riecke publishes a set of 1-dimensional differential equations for the conduction of electricity between concentric spherical electrodes and cartesian plane-parallel electrodes. These equations [15] contain terms that describe both the drift of the ions due to an electric field, as had been done by Thomson in 1899, and terms that describe the diffusion of the ions due to concentration variation in the gas. In addition, he proposed solving the differential equations by the method of successive approximation.

In 1932 KK Darrow [17], an American physicist working at AT&T's Bell Laboratory, extended Riecke's work by deriving and interpreting the differential equations for plane-parallel electrodes in his treatise titled *Electrical Phenomena in Gases* using modern notation. To simplify the mathematical discussion, consider 1-dimensional plane-parallel electrodes of separation d cm, a gas with relative permittivity $\varepsilon_r \approx 1$, and with no external magnetic field so that $\boldsymbol{B} = 0$. Let the gas be uniformly ionized at a rate of q ip·cm^{-3}·s^{-1}. Let n_1 cm^{-3} and n_2 cm^{-3} be the number of positive and negative ions per cubic centimeter of gas respectively. Let the drift mobility of the positive ions be μ_1 cm^2·V^{-1}·s^{-1} and the negative ions be μ_2 cm^2·V^{-1}·s^{-1} with $\mu_2 > \mu_1$. Let the positive and negative ion diffusion coefficients, D_1 cm^2·s^{-1} and D_2, be given by the Einstein relationship, $D = \mu k_{eV} T$, where $k_{eV} = k_B/e$ J·A^{-1}·s^{-1}·K^{-1} $\approx 8.61733(3)$ x10^{-5}eV·K^{-1} is the Boltzmann constant, $k_B := 1.380649$ x10^{-23} J·K^{-1}, divided by the elementary charge, e := 1.602176634 x10^{-19} A·s, T K is the absolute temperature of the gas ions, and $\varepsilon_0 \approx 8.854187(8)$ x10^{-14} A·s·V^{-1}·cm^{-1} is the permittivity of vacuum. The origin of the coordinate system's abscissa, x, is the positive electrode where a potential difference, ΔV V, will be assumed.

Let ρ be charge density, then from the differential form of Gauss' law (Maxwell's equation)

$$\textbf{div}\ \boldsymbol{D} = \nabla\cdot\boldsymbol{D} = \nabla\cdot\ \varepsilon_0\boldsymbol{E} = \rho \ ==> dE/dx = e\{n_1(\mathrm{x}) - n_2(\mathrm{x})\}/\varepsilon_0$$

so that the spatial derivative of the electric field is proportional to the difference in the density of the ions. Let $\boldsymbol{B} = 0$, then from the Maxwell equation

$$\textbf{curl}\ \boldsymbol{E} = \nabla\times\boldsymbol{E} = -\,dB/dt = 0 \ ==> \boldsymbol{E} = -\textbf{grad}\ \varphi = -\nabla\varphi ==> \Delta V = \int_0^{\mathrm{d}} \boldsymbol{E}(x)\,dx$$

thus, the voltage between the electrodes is the integral of the electric field in the gas.

Let the drift velocity of the ions be proportional to their mobility times the electric field, $\mathbf{v}_d = \mu\boldsymbol{E}$. Let Δn be the Laplacian expression $\Delta n = \nabla^2 n = \nabla\cdot\nabla\boldsymbol{n}$ Then, the conservation of charge equations for the positive and negative ions become:

$$\textbf{div}\ (n_1\boldsymbol{v}_1) = \nabla\cdot(n_1\boldsymbol{v}_1) = q - \alpha\, n_1 n_2, + D_1\Delta n_1,$$
$$\textbf{div}\ (n_2\boldsymbol{v}_2) = \nabla\cdot(n_2\boldsymbol{v}_2) = q - \alpha\, n_1 n_2 + D_2\Delta n_2,$$

For simplicity of presentation consider the conservation of charge equations in 1-D where: div $\boldsymbol{E}$ is $\partial E_x/\partial x$, $(1/r)\partial(rE_r)/\partial r$, or $(1/r^2)\partial(r^2E_r)\partial r$, Δn is $\partial^2 n\partial x^2$, $(1/r)(\partial/\partial r)[r(\partial n/\partial r)]$, or $(1/r^2)(\partial/\partial r)[r^2(\partial n/\partial r)]$, and $\boldsymbol{v}_1 = [\mu_1 E]$, $\boldsymbol{v}_2 = -[\mu_2 E]$ respectively. Then, subtracting the negative ion conservation of charge equation from the positive ion conservation of charge equation and integrating once with respect to x results in the current-density, j, equation

$$j/e = (n_1\mu_1 + n_2\mu_2)E - (D_1 d^2n_1/dx^2 - D_2 d^2n_2/dx^2) = I/Se\ \text{cm}^{-2}\cdot\text{s}^{-1},$$

where $j = I/S\ \text{cm}^{-2}\cdot\text{s}^{-1}$, I is the total measured cell current, and S is the common area of the electrodes. Note that the conduction of electricity through a gas is non-ohmic since because of the ion diffusion term and the ion drift term the current does not have to vanish when the cell voltage is zero.

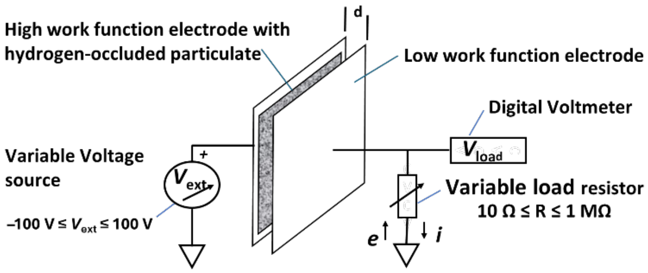


Figure 8 illustrates a parallel plate cell configuration of a LEC.

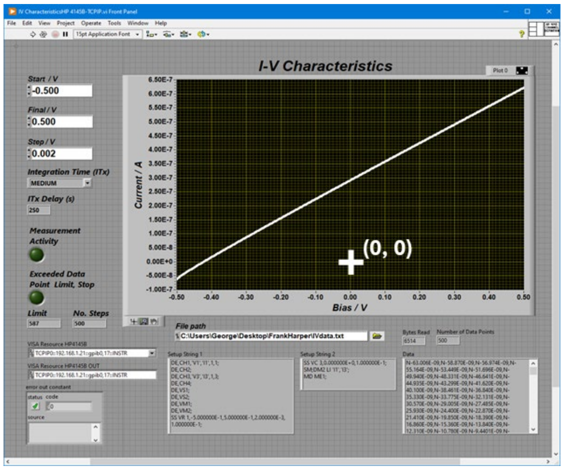
In Fig. 8, an external variable voltage source, V_{ext}, is connected to a gaseous LEC's high work function (HWF) or counter electrode (CE). A variable load resistor, R_{load}, connects the low work function (LWF) or working electrode (WE) to ground so that the current, $I_{\text{cell}} = V_{\text{load}}/R_{\text{load}}$, flowing through the cell can be measured. By measuring the difference in voltage between the CE and WE the differential cell voltage, $V_{\text{cell}} = V_{\text{ext}} - V_{\text{load}}$, across the cell can be measured. 'Active' hydrogen-occluded hydrogen host material (HHM), such as electrodeposited palladium (Pd) iron (Fe) [1-3], or their particulates, can also be used in contact with the electrodes and the gas between the electrodes. Either hydrogen gas (H_2) or deuterium gas (D_2) can be used, however, there is some indications that the HHM is more 'active' in allowing the cell to conduct a greater amount of current when deuterium gas is used. Typical LEC gas pressures range from one-half an atmosphere (~380 torr or 7.35 psia) to several atmospheres (~1520 torr).

When V_{ext} is greater than V_{load}, $V_{\text{ext}} >> V_{\text{load}}$, the 'activity' of a LEC cell can be estimated since the LEC is operating in a manner similar to that of an ionization chamber or in a mode similar to that described by Storms [9].

When V_{ext} is less than or equal to V_{load}, $0 \le V_{\text{ext}} \le V_{\text{load}}$, the spontaneous current produced by a LEC cell can be measured. It is important to note that the electrical conduction of a LEC cell is non-ohmic in the sense that a LEC cell can produce a current even when V_{cell} is zero. This behavior is suggestive that the gas in contact with the electrodes is acting like an electrolyte containing mobile ions and that it is the combined diffusion of the ions as well as their drift under the influence of the electric field in the gas that contributes to a LEC's experimentally measured load current. It is interesting to note that in contrast to the behavior of gas experiments reported by JJ Thomson in his treatise on the *Conduction of Electricity Through Gases* [28] where he used external ionizing radiation sources, the measured cell current of a cylindrical electrode electrodeposited palladium

(Pd) and deuterium gas cell did not ‘saturate’ as cell voltage increased to more than approximately 300 V [1].

When plating palladium (Pd) the initial Pd plating bath consists of 0.03 molar $PdCl_2$ and 0.15 molar LiCl in an aqueous solution of light water. As the plating process progresses the bath clears and more of the 0.03 $PdCl_2$ is added. After the plating of an electrode is finished a significant number of black Pd particles will settle out of the plating bath. When these Pd particles are separated from the bath and dried they will cause the same activity as electrodeposited Pd. A similar activity results from iron (Fe) particles separated from their plating bath. The unusual behavior of hydrogen or deuterium-occluded electrodeposited HHM or their particulates is a possible indication of quantum or Lattice Enabled Nuclear Reaction (LENR) activity.



Start / V: -0.500
Final / V: 0.500
Step / V: 0.002
Integration Time (ITx): MEDIUM
ITx Delay (s): 250
Limit: 587
No. Steps: 500
File path: C:\Users\George\Desktop\FrankHarper\IVdata.txt
Bytes Read: 6514
Number of Data Points: 500
VISA Resource HP4145B: TCPIP0::192.168.1.21::gpib0,17::INSTR
VISA Resource HP4145B OUT: TCPIP0::192.168.1.21::gpib0,17::INSTR
error out constant: status ✓ code 0 source

Setup String 1

```
DE,CH1,'V1','I1',1,1;
DE,CH2;
DE,CH3,'V3','I3',1,3;
DE,CH4;
DE,VS1;
DE,VS2;
DE,VM1;
DE,VM2;
SS VR 1,-5.000000E-1,5.000000E-1,2.000000E-3,
1.000000E-1;
```

Setup String 2

```
SS VC 3,0.000000E+0,1.000000E-1;
SM;DM2 LI 'I1','I3';
MD ME1;
```

Data

```
N-63.006E-09,N-58.870E-09,N-56.974E-09,N-
55.164E-09,N-53.449E-09,N-51.696E-09,N-
49.940E-09,N-48.331E-09,N-46.641E-09,N-
44.935E-09,N-43.299E-09,N-41.620E-09,N-
40.100E-09,N-38.461E-09,N-36.840E-09,N-
35.330E-09,N-33.775E-09,N-32.131E-09,N-
30.570E-09,N-29.005E-09,N-27.485E-09,N-
25.930E-09,N-24.400E-09,N-22.870E-09,N-
21.410E-09,N-19.850E-09,N-18.390E-09,N-
16.860E-09,N-15.360E-09,N-13.840E-09,N-
12.310E-09,N-10.780E-09,N-9.440E-09,N-
```

Figure 9 is a current-voltage (I-V) sweep of a coaxial LEC cell taken with a HP 4145 B Semiconductor Parameter Analyzer (SPA) that shows non-ohmic conduction behavior. Image curtesy of GL Kerber (GLK Instruments, San Diego).

The conduction of electricity by a gaseous LEC in the drift regime determines the magnitude of the shunt current lost from the load impedance, Z_L. In JJ Thomson’s 1899 publication [14] he extends the results that E Rutherford and he published in 1896 where they neglected space charge effects at the electrodes, *i.e.*, they assumed the electric field was the voltage between the electrodes divided by their separation, ℓ, and thus the current-density, i, was determined to be related to the voltage difference, ΔV, as $\alpha\ell^2 i^2/e^2(k_1+k_2)^2(\Delta V)^2 + i/\ell e = q$. In Thomson’s 1899 derivation, he writes:

> in this investigation I have tried to allow for the variation in the electric intensity [near the electrodes and find that $\Delta V = \mathrm{A}i^2 + \mathrm{B}i$]. The above investigation ceases to be an approximation to the truth when the two layers touch each other. In this case the current has its limiting value *lqe,* and there is no loss of ions by recombination; we may therefore neglect the recombination and proceed as follows. ⋯. If q is constant, ⋯ the boundary conditions [are] $n_1 = 0$ when $x = 0$, and $n_2 = 0$ when $x = \ell$.

Let $k_1 \neq k_2$, then $\mathrm{X}(d\mathrm{X}/dx) = 4\pi qe\{x[(1/k_1) + (1/k_2)] - \ell/k_2\}$, with solution $\mathrm{X}^2 = 8\pi qe\{(x^2/2)[(1/k_1) + (1/k_2)] - \ell x/k_2\} + \mathrm{C}$, Thomson considers space charge near the electrodes and finds that $\Delta V = Ai^2 + Bi$. Thus, the shunt current in a LEC increases as the square root of the cell's CPD voltage. However, he notes also that

> As the current through the gas increases the layers of inconstant X expand until they touch, and then there is no longer a region in which X is constant.

In his treatise, Darrow [17] observed that electrical conduction is non-ohmic in the sense that the current-density and the voltage do not have to go to zero simultaneously. This behavior is shown in Fig. 9 for an InovL LEC cell that has been operating continuously for more than eight years. The high work function electrode is electrodeposited palladium (Pd) on a 1/4-inch copper (Cu) tube. The low work function electrode is a 3/4-inch brass pipe nipple. The 'active' or ionized gaseous electrolyte is deuterium (D_2).

6. Kinetic theory of gases

The Kinetic Theory of Gases [19] provides a perfect (ideal) gas rational for the large numbers required to explain the large measured current-densities of experimental LEC and EDEC devices. Loeb enumerates four characteristics of the model of a perfect gas:

> (1) A gas consists of particles called molecules which in a stable state and in a given type of gas are all alike. The mass of the molecules will be denoted by m.
> (2) The molecules are in motion, and as they are material bodies Newton's laws of motion may presumably be applied.
> (3) The molecules behave as elastic spheres of diameter σ. In perfect gases the number of molecules in the space considered is small enough so that the mean distance between the molecules is large compared to their diameter, and thus for these elementary considerations the space they occupy may be disregarded.
> (4) In perfect gases no appreciable forces of attraction or repulsion are exerted by the molecules on each other or on the substance of the containing vessel.

Statistically, there is a distribution of speeds for the thermal motion of gas molecules. Figure 10 shows the Maxwell distribution of speeds for hydrogen (H_2) gas at three different temperatures: 25 K, 50 K, and 100 K. Note that as the temperature increases the fraction of molecules with a given speed decreases but that the maximum speed of the highest speed molecules increases.

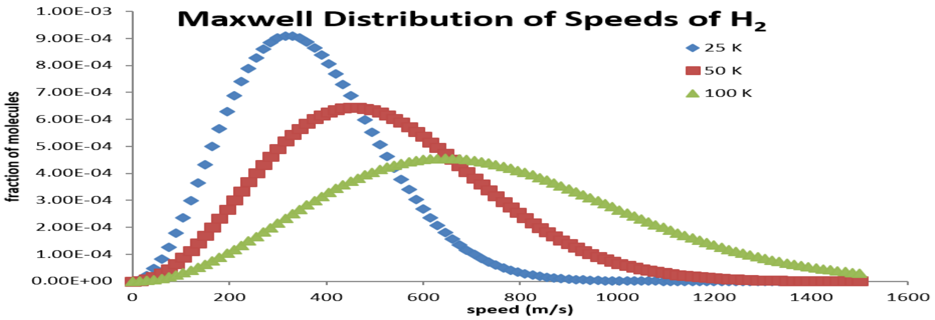


Figure 10 [29] shows three different Maxwell speed distributions for hydrogen (H2) gas as a function of absolute temperature: 10 K, 50 K, and 100 K. The ordinate gives the fraction of the molecules with the given speed shown by the abscissa. At a temperature of 0 °C and a pressure of 1 atmosphere the number of molecules in a cubic centimeter of gas is given by Loschmidt's number, $n_0 \approx 2.69 \times 10^{19}/\text{cm}^3$.

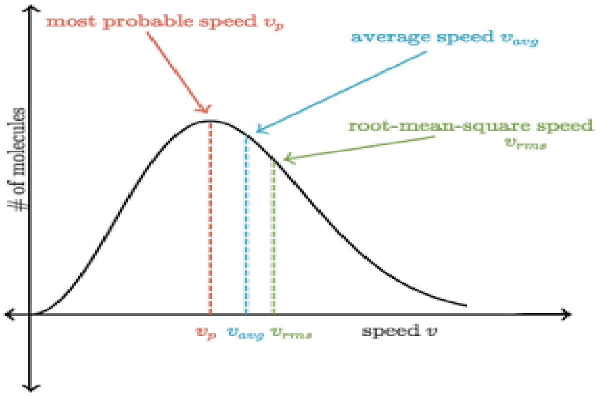


Figure 11 [30] shows number of gas molecules versus their speed, v, or celerity, c, for the Maxwell-Boltzmann distribution function $f(c) = 4\pi c^2(M/2\pi k_B T)^{3/2}\exp[-Mc^2/2k_B T]$. The three speeds are: (i) most probable, c_{mp} or v_{p}; (ii) average, $\langle c\rangle$ or v_{avg}; (iii) root-mean-squared, c_{rms} or v_{rms}.

The Maxwell-Boltzmann celerity distribution function, $f(c) = 4\pi c^2(M/2\pi k_B T)^{3/2}\exp[-Mc^2/2k_B T]$, where c is the celerity or speed of the gas molecules, M is their mass, k_B is the Boltzmann constant, and T is the absolute temperature of the gas molecules. Three speeds are defined: (i) the peak celerity, $c_{\text{p}} = (2RT/M)^{1/2}$, which is the speed of the largest number of gas molecules; (ii) the average celerity, $\langle c\rangle = (8RT/\pi M)^{1/2}$; and (iii) the root-mean-squared celerity, $c_{\text{rms}} = (2RT/M)^{1/2}$; where R is the 'gas constant', and M is the mass of the gas molecule. The average celerity, <c>, is the speed needed to compute the number of wall or electrode impacts per square centimeter per second and is approximately 13 % greater than the peak speed of the gas molecules at absolute temperature T.

In particular, some of the small fraction of the large number of molecules that impact a square centimeter of wall per second, that determines for the pressure of a confined gas, will have sufficient energy to exchange an electron from the high work function electrode to the electrolyte

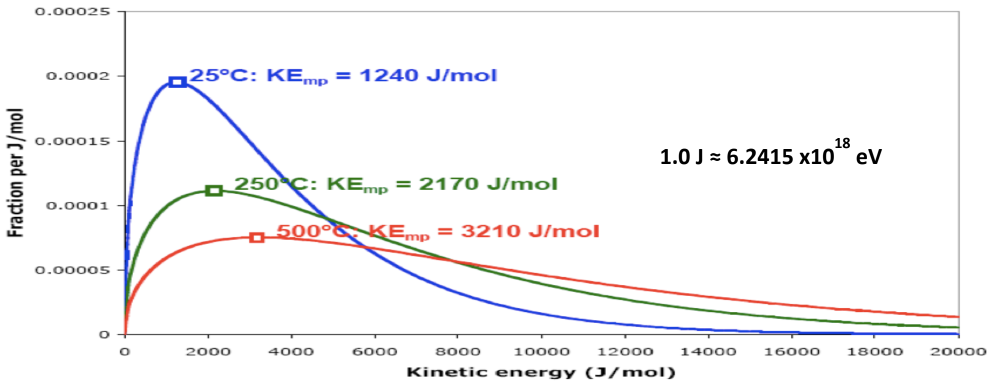


Figure 12 [31] shows the Maxwell-Boltzmann energy distribution as a function of absolute temperature *T*. Ordinate is the fraction of molecules with a given energy.

7. Summary discussion

The spontaneous generation and conduction of electricity by gaseous LEC devices is surprising to many engineers and scientists. In fact, the simplicity of the LEC or EDEC raises the question, “why wasn’t this discovered a long time ago?” The answer in large part is due to the success of the electrochemical battery and the fact that diffusion was considered to be insignificant. However, experimental results as well as the analytical model open the possibility of developing useful electrical power using EDEC devices.

The Kinetic Theory of Gases [19] provides an explanation of the large numbers required to explain the large measured current densities of experimental LEC and EDEC devices. In particular, some of the large number of molecules that impact a square centimeter of wall per second, that account for the pressure of a confined gas, will have sufficient energy to exchange an electron from the high work function electrode to the electrolyte, with the net effect that more negative charge is transported from the HWF to the LWF electrodes.

By using the Maxwell-Boltzmann statistical data, the projected current can be calculated. For hydrogen, H_2, gas at a pressure of 1 atmosphere and a temperature of 300 K, the number density of the gas is approximately 2.68 x10^{19} molecules/cm^3. The mean speed of the molecules is approximately 1773 m/s and this results in approximately 1.08 x10^{24} molecule impacts per square centimeter of electrode surface area per second. Assume that it takes an average energy of 1 eV or 1.602(1) x10^{-19} J to remove an electron from a high work function electrode that includes hydrogen-occluded palladium (Pd) hydrogen host material. If out of 1 billion molecules that impact 1 square centimeter of electrode surface area per second, the result is 1 electron being removed from the high work function electrode and transported to the low work function electrode then approximately 1.08 x10^{15} electrons are transferred from the low work function electrode to the high work function electrode and the LEC’s current density is approximately 173 μA/cm^2. This result is close to the 7 X 10^{14} electrons per second per square centimeter that was shown in FIG 2. Similar results are possible for EDECs using liquid, gel, solid, or solid-state electrolytes. Thus, the LEC/EDEC stochastic model or hypothesis describes the conditions needed to realize the experimentally measured current densities.

The stochastic EDEC model presents several opportunities to increase EDEC power density output. Activation energy can be reduced by using working electrodes that include hydrogen-occluded metal particulates; by reducing the separation distance between the electrodes; and by using materials with larger work function differences. Electrolytes can be improved by using mixtures of gases; by using liquids or gels as long as precautions are taken so that the liquids or gels do not react chemically with the electrodes. Various techniques such as using gas electrolytes, high temperature epoxies, or even semiconductor materials such as p-n junction photovoltaics can minimize electrochemical reactions.

The possibility that LENR might be involved should be considered, since although LENR is not required by the stochastic electrophysical model, EDEC cells constructed without 'active' HHM have power outputs that are below our ability to measure the power. Additionally, experimental LEC tests indicate low activation energies that are hard to explain based only on thermal input to the devices.

8. Concluding remarks

The model analysis and supporting experimentation identifies several opportunities to improve LEC power output. The analysis was for gas but other 'electrolytes' including water, ethylene glycol, electrode gel, high temp epoxy, and solid-state materials have been successfully used. Device configurations similar to electrolytic capacitors have been constructed which successfully produced a voltage and current. Additionally, both gaseous LEC or liquid, gel, and solid-state EDEC design simplicity could lead to rapid production of low cost, safe, green energy devices for the world.

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